COOP AGREEMENT Colorado State

Review Draft

PROCEDURES RECOMMENDED FOR OVERBURDEN AND HYDROLOGIC STUDIES OF SURFACE MINES

FINAL REPORT

PART I

SEAM THUNDER BASIN STUDY

Prepared by

James Barrett, Paul Deutsch, Frank G. Ethridge, William T. Franklin, Robert D. Heil, David B. McWhorter, and Daniel Youngberg

COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO 80523

and

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Authors

Dr. David B. McWhorter and Mr. James Barrett
Dept. of Agricultural and Chemical Engineering
Colorado State University
Fort Collins, Colorado 80523

Dr. Frank G. Ethridge
Dept. of Earth Resources
Colorado State University
Fort Collins, Colorado 80523

Dr. William Franklin, Dr. Robert Heil, and Mr. Paul Deutsch
Dept. of Agronomy
Colorado State University
Fort Collins, Colorado 80523

Mr. Daniel Youngberg
U. S. Forest Service
809 South 9th Street
Douglas, Wyoming 82633

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I. RATIONALE AND PROBLEM IDENTIFICATION

Thorough analysis and planning for reclamation of lands disturbed by surface mining and for the control and mitigation of potential water quality degradation can preserve the long-term productivity of the land and the integrity of the water resources without undue hinderance to the development of mineral resources. This goal can be achieved through evaluation of the characteristics and interrelationships of soils, overburden, surface water and ground water; thereby permitting rational assessment of alternatives for exploration, mining, and reclamation activities.

The Surface Environment and Mining Program (SEAM) of the U. S. Forest Service was given funds to develop recommendations and criteria for the study of soils, overburden, and hydrology at surface mining sites. Two basic goals were established for the project:

1. Determine the kinds of information required to evaluate the soils, overburden, and hydrology so that appropriate land management decisions can be made relative to the selection of lease sites, development of lease stipulations, and formulation of mining and reclamation plans.

2. Recommend cost effective procedures for data acquisition and analysis associated with soils, overburden, and hydrologic studies.

The objectives are achieved by defining soils, overburden, and hydrologic information requirements and by evaluating and prioritizing alternative approaches to sampling and analysis where possible. The purpose is to assist in making leasing, mining, and reclamation decisions that give due consideration to surface stability, soil and overburden fertility, occurrence and distribution of toxic materials, surface and

ground water quality and quantity, and future land and water uses. The information requirements and procedures for analysis are derived with the recognition that the chemical mineralogical, and textural characteristics of soils and overburden effect fertility, stability, weatherability, erosion, water quality, runoff and recharge. Also, the data needs that were developed reflect the requirement that the relationships among topography, geology, climate, vegetation, surface water, ground water, water quality, and water use must be adequately understood.

This handbook has been prepared as a result of the SEAM study. No attempt was made to identify all available technology and information available for the study of soils, overburden, and hydrology; but rather to recommend proven methods and procedures that are known to give good results. References are cited so that the reader can obtain more detailed information when desired.

II. DATA REQUIREMENTS AND COLLECTION PROCEDURES

A. Sources of Existing Data

1. General Sources of Data

From mining company standpoint, the information required for a literature review must include knowledge of the various disciplines which influence property evaluation. For an initial literature review the available data in the following areas should be examined: a) geology, b) hydrology, c) soil science, d) environmental science, e) legal, and f) mining. Such data can be extracted from numbers of sources including government agencies, technical journals and books, university publications, and private sources. Sources of information in the areas, excluding legal and mining will be covered in detail below.

Appendix I is a list of sources for geological, hydrological, soils, and reclamation data. This list is modified extensively from Peters (1978). Most of the sources can be found in University libraries and all of the geological references are available in the USGS Library in Denver, Colorado. Perhaps the best general source for geological information is the book by Wood (1973). The best overall source of information on the collection of subsurface data and the analysis of subsurface samples is LeRoy et al. (1977). State geological surveys and/or bureaus of mines should always be consulted at an early stage for geological information on a particular local area. A list of state geological surveys in the Rocky Mountain Region is included as Appendix II.

2. Unpublished Data Sources

Most federal and state bureaus of mines and gological surveys have preliminary reports, project files, and raw numerical data on open file for public inspection. Open file reports of the U. S. Geological Survey

and the U. S. Dept. of Energy can be examined in Denver, Colorado. Copies of these reports can often be obtained for the cost of xeroxing.

Detailed unpublished material on conservation and management practices are available at local Soil Conservation Service Offices. Also available are lists of important and prime farmland that may occur in each county or planning unit.

The Forest Service and Bureau of Land Management have management plans which contain information on existing resources within certain management units of public lands. This information is available for public inspection.

3. Computerized Data Banks

As the wealth of knowledge in various scientific disciplines becomes greater, there is an ever increasing need for computerized data banks to handle storage and retrieval of this information. Some of the more important geological data banks are given below:

RASS, Rock Analysis Storage System. Used within the U.S. Geological Survey. Files not available to the public, but some data are released on magnetic tape. Washington, D.C.

SSIE, Smithsonian Science Information Exchange; information on research in progress: Washington, Smithsonian Institute.

CRIB, Computerized Resources Information Bank, Used within the U.S. Geological Survey, Washington, D.C.

DATRIX, Direct Access to Reference Information, Theses and Dissertations: Ann Arbor, Michigan, University of Michigan.

Geo-Archives: London, Geosystems (Lea Associates Ltd.).

GEODAT, numerical results produced by laboratories in the Geological Survey of Canada, chemical, spectrographic, and age data. Available to users in the private sector. Geological Survey of Canada, Ottawa.

Geo Ref, a geoscience-oriented service provided by the American Geological Institute and the Geological Society of America; files date from 1966.

GRASP, Geological Retrieval and Synopsis Program. Used within the U.S. Geological Survey, Washington, D.C.

4. Sources of Maps and Aerial Photographs

a. Topographic Maps

About 90 percent of the United States is covered by 1:62,500 (15-minute quadrangle) to 1:24,000 (7-1/2-minute quadrangle) topographic mapping. Indexes to topographic mapping in each state are published quarterly by the U.S. Geological Survey. These and the topographic maps are obtainable by mail from the U.S. Geological Survey Offices in Denver, Colorado, for the western states. Copies of U.S. Geological Survey topographic maps and advance prints of preliminary quadrangle maps are also available (although not by mail) from District U.S. Geological Survey offices and from State Geological Surveys and Bureaus of Mines at the addresses shown by Wood (1973), and Ward and Wheeler (1972).

b. Geology, Geophysics, and Soil Maps

Government geologic mapping in the United States covers most of the country at a scale of 1:500,000 (state maps), about 40 percent of the country at a scale 1:250,000 and about 25 percent of the country at 1:62,500 to 1:24,000. Unlike topographic mapping, some of this has been done by the State Geologic Surveys. In addition, some areas have been mapped for universities by candidates for advanced degrees. Even though the maps are scattered through federal, state, and scientific association publications, most states have an updated index to geologic mapping compiled by the U.S. Geological Survey or by the state bureau of mines. Special map series produced by the USGS include:

Coal Investigation Maps
Geologic Quadrangle Maps. This series is a continuation of the Gelogic Folios published between 1894 and 1946.
Geophysical Investigations Maps. This series includes aeromagnetic and rediographic maps at 1:62,500 and 1:24,000 scale.
Hydrologic Investigations Maps.
Mineral Investigations Field Studies Maps. This series includes preliminary tectonic, metallogenic, mineral deposits, and geological maps.

Mineral Investigations Resource Maps. These are mineral deposit maps.
Miscellaneous Geological Investigation Maps. This series includes photogeologic maps, and paleotectonic maps.
Oil and Gas Investigations Maps.

Detailed soil inventories conducted by the Soil Conservation Service, Bureau of Land Management and the Forest Service are available for certain areas throughout the western United States. Information is available at these agencies' state or regional offices. State general soil maps with scales of about 1:500,000 and county general soil maps and prime farmland maps with scales of 1:100,000 to 1:250,000 are, or will be available from the Soil Conservation Service in each western state.

c. Aerial Photographs and Spacecraft Imagery

Aerial photography coverage in the United States is shown on the U.S. Geological Survey quarterly indexes to topographic mapping for each state. Smaller scale indices to aerial photography coverage of the entire country are also published from time to time. Indices and advice on coverage by government agencies for specific areas can be obtained from the National Cartographic Information Center, U.S. Geological Survey, National Center (STOP 507), Reston, Virginia 22092.

The U.S. Geological Survey EROS Date Center, Sioux Falls, South Dakota 57198, is the source for copies of geological survey aerial photographs, NASA photography and imagery, Landsat Imagery, and Skylab photography and imagery. (The abbreviations here are: EROS = Earth Resources Observation Systems; NASA = National Aeronautics and Space Administration; and Landsat = the former ERTS, Earth Resources Technology Satellite.) Satellite imagery is available on magnetic tape and in photographic form. Standard catalogs and film strips as well as transparencies, paper prints, enlargements and state image maps are available. A geographic search and inquiry system provides free information on

specific photographic coverage. EROS application assistance facilities and data reference files are located at more than a dozen offices throughout the United States.

B. Field Surveys

1. Geologic Overburden

The primary objectives of field reconnaissance are to verify the existing data and to seek out new field data that might have been overlooked by previous workers.

The verification of existing data is accomplished by field examination of outcrops, roadcuts, active and/or abandoned mine workings, and stored cores and geophysical logs. No new drilling or test pit work is undertaken during these surveys. The final products of a field survey will probably constitute detailed geologic and topographic maps of the proposed mine area at an appropriate scale. Other information plotted on surface maps will include borehole and pit locations, access routes and surface drainage.

2. Soil

a. Definition of the Soil

Basic to determining the kind and intensity of inventories necessary to provide information needed by planners and resource managers involved in reclamation planning, is a definition of the resource being inventoried. "Soil," as conceived by some, consists of the unconsolidated materials found near the earth's surface. The diagram shown in Figure 1 illustrates that the above definition is incorrect. The schematic soil profile shown in Figure 1 reflects the effect of various chemical, physical, biological and translocation processes that have taken place through time. These processes give rise to layers that are significantly

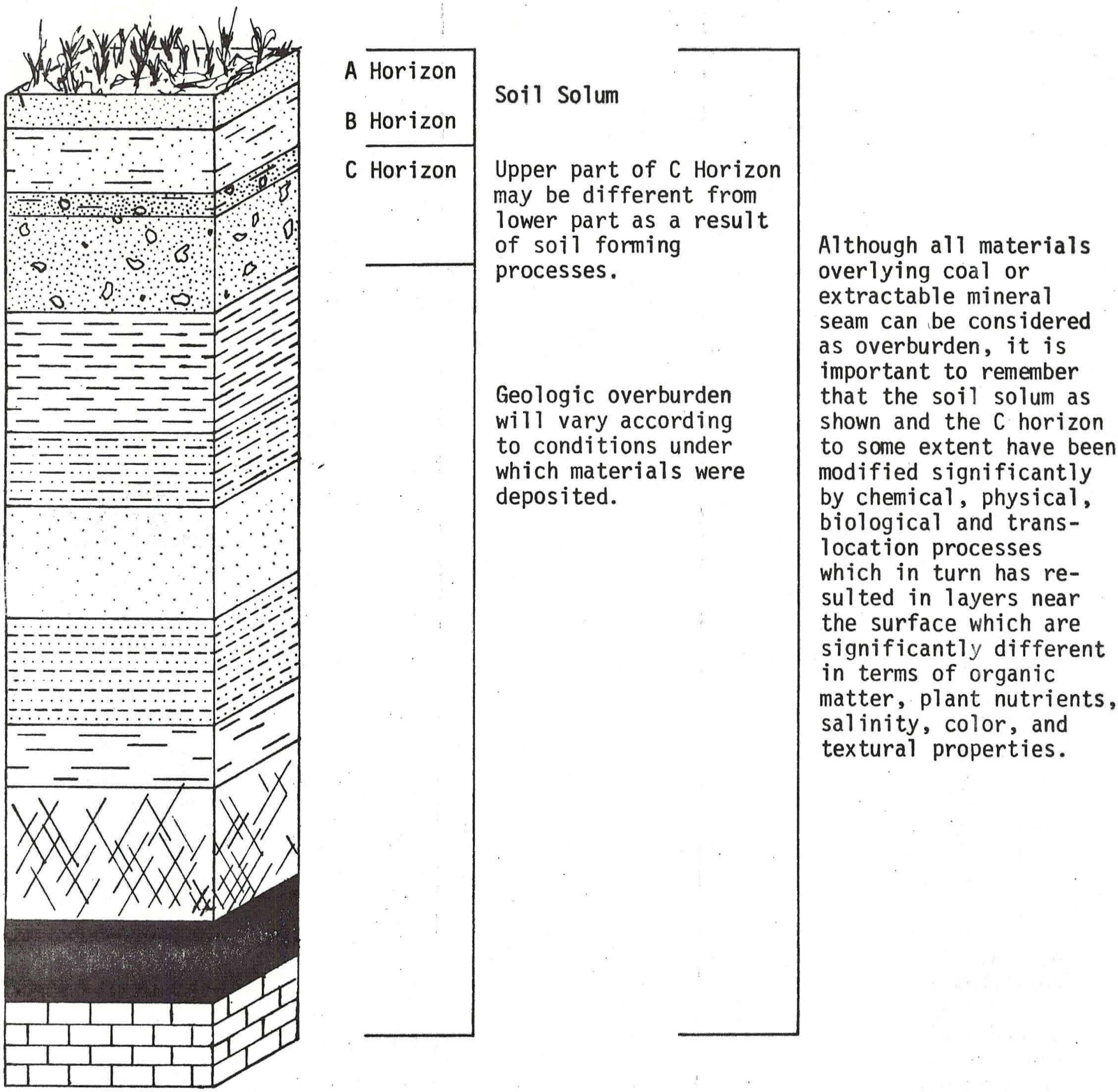


Figure 1. Schematic illustration of the relationship between soil and geologic overburden.

different in terms of their chemical, physical, and biological properties. These differences in basic properties in turn affect other characteristics such as plant nutrient status, water holding capacity, erodibility, infiltration, and permeability properties which are very important in assessing the opportunities and/or constraints that soils offer in developing management alternatives for reclaiming a tract of land which will be disturbed by mining activity.

The concept of soil used in developing a soil inventory plan is one which utilizes an approach that recognizes soil layers. This approach ensures greater reliability for separating natural soil bodies into groups which are different, and prevents mixing or grouping of unlike soils and allows for maximum utilization of existing soil data. Separation into genetic horizons is extremely critical in sampling for laboratory analyses.

This distinction in considering soil different from the remaining overburden material is enhanced when considering that in most cases the soil, and most often the "A" horizon materials possess more characteristics which are suitable for plant growth than do materials below. Thus it is critical to evaluate these upper layers of the earth's crust.

b. <u>Purpose of Soil Inventory</u>

The purpose of a soil inventory is to provide answers to the following questions:

1. What land capabilities exist at the present time? Prime, important, and unique farm lands need to be identified along with the agricultural productivity potential of the area.

2. What opportunities and/or constraints do soils offer for developing management alternatives for reclaiming a tract of land to be disturbed by surface mining?

In order to a wer these questions, it follows that the soil inventory must identify:

1. The different kinds of soils that occur, based on physical, chemical, and depth characteristics as well as other features which affect use such as slope, stoniness, etc., and

2. The area extent and distribution of soils as exhibited on a soil map.

The discussion that follows provides information that can be used for determining the kind and intensity of soil inventory that would provide land managers, planners and mine operators with the kind of soil information needed in developing a reclamation plan.

c. Design of Soil Inventory

The design of a soil inventory program should consider the following factors:

(1) Map scale and survey intensity,

(2) Soil description procedures,

(3) Soil mapping unit description procedures,

(4) Soil classification and correlation,

(5) Sampling.

(1) Map Scale and Intensity

Information shown in Table 1 summarizes the relationships between soil inventory intensity and level of detail at which "map unit delineations" are recognized and soils are classified. The information shown is a general guideline used by the Soil Conservation Service in planning for soil inventory intensity. Information shown in Table 2 shows similar guidelines as developed and used by the U.S. Bureau of Reclamation for making irrigation suitability inventories. Perhaps the most important

Table 1. Relationships of soil inventory intensity and level of intensity at which map unit delineations are recognized and soils are classified.

	ORDER 1	ORDER 2	ORDER 3	ORDER 4	ORDER 5
TAXONOMIC CLASSIFICATION	Series	Series	families and series	families and subgroups	subgroups, great groups, suborders and orders
MAP UNIT	phases of soil series	phases of soil series	phases of soil series and soil families	Associations with some consociations	Associations
MAP SCALE NEEDED	1:12,000 and larger	1:12,000 to 1:31,680	1:24,000 to 1:250,000	1:100,000 to 1:300,000	1:250,000 to 1:1,000,000
SMALLEST UNIT MAPPED	less than 1.5 acres	1.5-10 acres	6-640 acres	100-1,000 acres	640-10,000 acres
% DISSIMILAR INCLUSIONS	less than 10%	less than 20%	less than 30%	not set in advance	not set in advance
ACCEPTED USES	experimental plots and individual home sites ...the nearest survey intensity to being site specific	planning of moderately intensively used management units, based on predictions of the suitabilities and soils response to management	planning for extensive uses of land such as rangeland, watershed management, woodland, and extensive kinds of cropland...county, multicounty, or watershed planning	regional planning within multicounty or multistate areas or larger watersheds... used to locate areas having potential for 2nd order survey and for site management planning	used for broadest kinds of planning for states or nations...accurate identification of most important soils and reasonable estimates of their extent
FIELD METHODS	Identification of soils of each delineation by direct examination of all boundaries throughout their lengths. Sampling plan of grid applied at random, in addition to soil examinations at places dictated by surface features that may mark soil differences. Laboratory determinations on samples collected at selected places to verify or augment field observations.	Identification of soils by transecting and transversing. Soil boundaries are plotted by observation and interpretation of remotely sensed data. Boundaries are verified at closely spaced intervals.	Soils in each delineation are identified by transecting and transversing and some observation. Boundaries are plotted by observation and interpretation by remotely sensed data and verified with some observations.	The soils of delineation representative of each map unit are identified and their patterns and composition determined by transecting. Subsequent delineations are mapped by transversing, by some observation, and by interpretation of remotely sensed data verified by occasional observations. Boundaries are plotted by air photo interpretations.	The soils, their patterns, and their composition for each map unit are identified through mapping selected areas (15 to 25 sq. mi.) with 1st or 2nd order surveys, or alternatively, by transecting. Subsequently, mapping is by widely spaced observations, or by interpretation of remotely sensed data with occasional verification by observation or transversing.

Table 2. Some Minimum Map Scale and Observation Requirements for Land Classification as used by the U. S. Bureau of Reclamation in Determining Irrigated Land Suitability

Specification	Reconnaissance Map	Semi-Detailed Map	Detailed Map
Scale of base maps	1:24,000	1:12,000	1:4,800
Land classes recognized	1,2,3,6	1,2,3,6	1,2,3,4,5,6
Maximum distances between traverses (miles)	1.00	0.50	0.25
Accuracy (%)	75	90	97
Field progress per day for one land classifier and crew (square miles)	3.00-5.00	1.00-3.00	0.25-1.00
Minimum soil borings or pits per square mile (5' deep)	1	4	16
Minimum number of deep substrata holes per township (10' deep or more)	1	2	4

Source: U. S. Bureau of Reclamation, 1953.

Detailed land classification (Bureau of Reclamation, 1953) is generally done at a map scale of 1:4,800 (400 feet to the inch) to provide adequate information as to the extent and character of the various lands in each 40-acre tract. A smaller scale, not less than 1:12,000, may be used on fully developed areas or on highly uniform new land areas where no specific problems are associated with soils, topography, or drainage and none are anticipated. Base maps at scales of 1:24,000 are considered only for reconnaissance studies by the Bureau, and are used for preliminary elevations and for drainage basin studies (e.g., runoff, conservation) of areas not to be irrigated, but within the general project area.

Results of soil profile examinations and laboratory analyses are also put on the map where appropriate. Field surveys are generally supplemented with extensive laboratory analyses, greenhouse studies, and field experimental plot data to obtain as much information as is needed before the irrigation project is implemented. Reports summarizing the data accompany the maps at the various scales.

Although the Bureau of Reclamation's irrigation suitability classification sets up specific limits for classes and subclasses, the specifications are not absolutely rigid, and can be modified from one project area to another. (Olsen, 1974)

factors as shown in the two tables are the "size of area" that is delineated on a map as a function of scale and the level of abstraction at which soils and/or land information is defined. Except for using the equivalent of an Order 3 (Table 1) type inventory for general planning, it appears that an inventory equivalent to Order 1 or 2 is necessary if all soil data needed in developing mined land reclamation planning is to be identified. The planner or land manager must decide on the intensity of the inventory needed based on the desired level of planning.

(2) Soil Description Procedures

Purpose: Soil profile descriptions are useful for identifying changes with depth in terms of soil texture, structure, presence or absence of calcium carbonate, color, and thickness of individual soil layers or horizons. These characteristics are important for assessing the opportunities that soils offer in developing alternative management plans. The form shown in Table 3 could be used in describing soil profiles. The form suggests that information in addition to soil characteristics be obtained. The purpose of this is to allow for coordination of soil data with other resource data collected. This maximizes the credibility of interpretations that are made from the data. Procedures for describing soil profiles can be found in Soil Taxonomy, (Soil Survey Staff, 1975) and Soil Survey Manual (Soil Survey Staff, 1951).

Using the above approach provides a basis for identifying the different kinds of soils found on a tract of land, aids in separating soil horizons for the purpose of sampling for laboraotry analyses and provides basic data needed for classifying the soils.

(3) Soil Mapping Unit Description

Purpose: A soil mapping unit describes the areal proportion of soil found, soil topography relationships, and other soil related features

TABLE 3. SAMPLE FORM FOR SOIL PROFILE AND RELATED INFORMATION.

Soil Type or Designation: File No.

Date | Stop No.

Classification

Location

Climate

Parent material

Physiography

Drainage | Salt or alkali

Elevation | Gr. water | Stoniness

Slope | Moisture

Aspect | Root distrib.

Erosion: Type | Degree:

Native vegetation (or crop)

Additional notes

Hori-zon	Depth	Color			Tex-ture	Struc-ture	Consistence			Reac-tion	Bound-ary	% Coarse Fragments >2 mm.
		Dry	Moist				Dry	Moist	Wet			
			non-crushed	crushed								

that occur on the landscape. The mapping unit becomes the basic unit from which management plans are developed, thus it needs to be accurately defined. Factors that should be included within the description include:

(1) Soil composition, i.e., homogeneity of unit;

(2) Degree and configuration of slope on which unit occurs;

(3) Existing or potential erosion characteristics;

(4) Brief description of the physical characteristics of the soil; such as, texture, structure, drainage, depth, permeability, infiltration, and any chemical characteristics;

(5) Identify native vegetation or type of crop; and

(6) Identify water table relationships if present.

Following are definitions of types of soil mapping units as developed by the Soil Conservation Service, USDA. (Soil Survey Staff, 1975)

Consociations - These are mapping units in which only one kind of soil dominates each delineation to the extent that three-fourths or more of the soils fit within the criteria defined for the soil that provides the name for the mapping unit. No one contrasting inclusion may constitute more than 10 percent of the unit and the aggregate of all contrasting inclusions may not exceed 15 percent.

Complexes - These are sets of delineated soil areas with two or more important components in such an intricate geographical pattern that they cannot be mapped separately at a scale of 1:20,000. The component kinds of soil that provide the name for the mapping unit have sufficiently different use or management requirements for the purposes of the survey that the unit cannot be named as a consociation. No single inclusion that is dissimilar to any one of the soils providing the name for the mapping unit may exceed 10 percent of the whole and the aggregate of these not more than 25 percent.

Associations - These are sets of delineated areas in which two or more important kinds of soil or soils and kinds of miscellaneous areas are found in some regular pattern and are individually large enough to be mapped separately at a scale of about 1:20,000. Ideally, occurence of a soil association normally has approximately the same major components and the potentials for use and management of the individual areas are about the same. However, as the intensity of the survey decreases, i.e., Order 4 vs. Order 3, the composition and distribution of soils may vary considerably both within the same occurrence and among occurrences of the same association. This is particularly true for older surveys.

In summary, the purity and homogeneity of mapping units is a function of the level of intensity or detail of a soil inventory. Land managers and planners need to be aware of this fact when using and planning for soil inventories. This is a very important item because the information contained within a mapping unit description is the basis for making decisions on land management units.

(4) Soil Classification and Correlation

There has been in the past and continues to be disagreement relative to classifying soils by various classification schemes. Most notably, questions are raised regarding the taxonomic classification of soils. Major considerations for classifying soils taxonomically and/or by interpretive classifications can be described as follows:

1) In order to utilize existing soil characterization and interpretive data, soils must be classified according to systems that have been used in assembling and storing data that has been collected in the past. If existing acceptable soil taxonomic and/or interpretive classification systems are utilized then it is possible to retrieve and utilize existing information in making interpretations.

2) Classification and correlation of soils allows for this information to become part of a soil data bank that can provide information for future utilization by others in other geographic areas. Through time, this will not only begin to decrease the amount of effort in data analysis, but will aid in improving the reliability of interpretations. Soil classification, either both by taxonomic and interpretive classification systems, is the key mechanism for knowledge assimilation and transfer.

(5) Sampling

Information relative to considerations that whould be kept in mind in sampling for analysis and classification of soil resources is shown in Table 4.

(6) Using Existing Soil and/or Land Inventory Data

Soil and land inventories have been carried out by a number of agencies for a number of years. For example, soil surveys made as early as the 1920's are available for some parts of the western United States.

The purpose of this section is to develop an awareness of the fact that past and existing soil and land inventories have been carried out at different scales of study and/or according to different concepts. This has resulted in soil and land inventory data that in some cases is applicable to making interpretations for many uses and in other cases are applicable to a particular use of level of planning. Add to this the fact that soil and land classification procedures and concepts have changed through time even within an agency, and we have a situation where it is critical that existing inventory data needs to be carefully evaluated for its credibility and reliability. This is not to infer that these data are not useful, rather we are saying that a given set of inventory data should be evaluated by the agency which made the inventory

Table 4. Summary of factors important for consideration in sampling for soil characterization and sampling.

Determining Need:	Samples for laboratory characterization and classification.
Selecting a Location:	Duplicate and/or paired profiles should be identified for each of the different soils which occur on a tract of land. Sampling paired profiles minimizes the chance of error. Sites should be representative of the soil in question and located within a mapping unit representative of the soil. Site should also reflect dominant land use.
Sampling Procedures:	Bulk samples for laboratory analysis and classification should be taken from each genetic horizon. (A, B & C horizons). Estimates and/or measurements should be made of the amount (by volume) of coarse fragments present. Material sampled for laboratory characterization should include mainly the fine earth fraction i.e., <2 mm. Approximately 5 to 8 lbs. of material is needed for laboratory characterization. Material collected for classification and correlation purposes should include natural aggregates and the amount necessary is normally less than ½ lb. Clod samples can be taken if bulk density and/or mineralogical analyses are to be performed. Samples should be obtained from an open pit. Depth of sampling should be to 60 inches or depth of bedrock if bedrock occurs at <60 inches. Sampling should start with the lowest layer in the pit and proceed upward. Samples of surface soil should include a composite of a number of samples taken from within a mapping unit as well as from the surface material sampled from pits. This will provide an estimate of the mean of the surface soil conditions of the area. A rule of thumb is that one composite sample should not represent an area more than 40 to 80 acres in size. An average of 10 to 15 subsamples per 40 acres should be taken depending on how variable the area may be.
Special Considerations:	If NO_3-N is to be determined, samples should be air dried as soon as possible after sampling. Otherwise, the NO_3-N determination more than likely will not reflect existing levels in the soil. Samples taken for heavy metals or micronutrient analyses should be protected from contamination. Rusty tools, galvanized or brass containers should not be used. Brown paper sacks should not be used if boron is to be determined. Plastic bags are most desirable for use. Samples taken for classification and correlation should be separated at time of sampling.

to determine the purpose of intended use for and concepts under which the survey was made.

If this is not done, the result is that the user may ultimately decide that the inventory is of no value, when in fact it may be useful if properly interpreted by someone familiar with it.

3. <u>Surface Hydrology</u>

Surface water hydrology investigations are undertaken to determine the location, magnitude, and movement of surface water in an area so that a water balance or budget can be developed. The water budget is an attempt to integrate the components of the hydrologic system (ground water, surface water atmosphere, and soil) into a physical model. This model is used to estimate the system response to land surface modification brought about by surface mining. Other objectives of a surface water investigation are to determine the surface water quality and quantity, its social and economic importance and potential impact on the resource and its users.

To achieve these objectives the following information is needed:

a) Detailed location of all surface water features,

b) Topographic relief of the area,

c) Aerial distribution of soils and surficial geology,

d) Vegetation cover and distribution,

e) Magnitude and frequency of precipitation events,

f) Stream flow,

g) Sediment discharge.

A brief discussion of each of these data needs follows.

a. Location of Surface Water Features

Surface water features include all wet or dry creeks, gullies, ditches, rivers, ponds, lakes, etc.. These features should be plotted on 7-1/2 minute topographic maps (scale 1:24,000). From these plots, determinations of the surface water flow directions, proximity of surface water features to proposed construction sites and appurtenances, and the drainage system morphology can be made.

The drainage system morphology can provide qualitative insights to the stratigraphy and geologic structure of the area as well as channel response to various precipitation events (Zernitz, 1932). Schumm (1977) states that drainage density (the sum of channel lengths per unit area) is proportional to the sediment yield and mean annual runoff. In other words, when subjected to an equivalent precipitation event, areas of dense channel development (common in arid regions) will have higher sediment yields, and greater peak discharge rates than sparsely channeled regions. Drainage density can also be related to the areal infiltration capacity of the ground surface. Low infiltration areas tend to have high drainage densities whereas high infiltration capacity soils tend to have lower drainage densities (Schumm, 1977).

b. Topographic Relief of the Study Area

USGS 7-1/2 minute topographic quadrangle maps are the best source of relief information. For a given precipitation event, peak runoff rates, sediment transport, and erosion rates are proportional to relief; base flow rates, and rainfall-runoff ratios are inversely proportional to relief.

c. Area Distribution of Soils and Surficial Geology

T his information may be obtained from geology and soils maps or by field reconnaissance. The following qualitative relationships can be

evaluated from geology and soils information;

1. Structural control of the drainage system.

2. High drainage densities are associated with easily erodible materials (Schumm, 1977).

3. Low drainage densities are associated with permeable materials (Schumm, 1977).

4. High erosion rates and sediment yields exist in areas of easily erodible materials.

In addition, knowledge of the distribution of permeable materials may aid the location of potential ground water recharge areas.

d. Vegetation Cover and Distribution

Vegetation density may provide insights as to the climate of the area, that is, the magnitude and frequency of precipitation events and drainage system response. In general, sparsely vegetated areas may be indicative of arid climate conditions with high peak flow rates and sediment yields. Densely vegetated areas retard runoff velocities thus reducing sediment yields and peak flow rates while increasing base flow.

e. Magnitude and Frequency of Precipitation Events

Channel morphology, relief, and vegetation cover reflect the nature or precipitation over a given area. Arid areas exhibit high relief, rugged topography and sparse vegetation generally representative of infrequent, torrential precipitation events. On the other hand, humid areas tend to have gentle topography and dense vegetation representative of many moderate precipitation events. In general, sediment load and erosion rates are higher in arid areas than in humid areas. Areas of infrequent, intense storms may have drastic fluctuations of surface water quality in response to the change in flow rate. Areas with extreme

discharge and water quality fluctuations require higher monitoring frequencies in order to accurately monitor the hydrologic system. Obviously, higher sampling frequencies lead to greater monitoring costs.

f. Stream Flow

Stream flow can be determined by the use of chutes, weirs, flumes, horizontal pipes, and velocity measurements; a detailed discussion of these methods follows.

Chutes - A chute is a steep channel of such high gradient that uniform flow takes place at less than the critical depth (Metcalf and Eddy, Inc., 1972). Flow in chutes is determined by Manning's equation:

$$V = \frac{1.486}{n} R^{2/3} S^{1/2}$$

where V = flow velocity (ft/rec)

S = slope of water surface (ft/ft)

n = Manning's roughness factor

R = hydraulic radius.

Once the flow velocity is determined, discharge is calculated by Q = VA where A = cross-sectional flow area (width x depth).

Weirs - Weirs are a very accurate means of flow measurement. This discussion deals with three common weir types; rectangular, triangular, and trapezoidal. The following conditions must be met in order to achieve accurate flow measurements (Albertson et al., 1960):

1. The weir plate must be vertical with a smooth upstream face.

2. The crest must be horizontal and perpendicular to the flow direction.

3. The crest should be fairly sharp and free of dents or bends.

4. The channel should be straight with uniform cross-section upstream and downstream of the weir location.

5. The sides of the channel should be smooth and vertical.

Flow over a rectanbular weir can be determined from Table 5 or by the following equation (Albertson, 1960):

$$Q = (3.22 + 0.4\ h/p)(L - 0.003)(h + 0.003)^{3/2}$$

where h = head on the weir (ft)

L = length of the weir crest (ft)

p = height of the weir (ft)

Q = discharge (ft^3/min).

The trangular weir is useful for channels with wide variations in discharge. Flow over triangular weirs can be determined from Table 6 or with the following equation (Albertson et al., 1960):

$$Q = 2.5\ h^{5}/2 \quad \text{(for right-angle notch only)}$$

where h = upstream water surface height above the weir crest (ft)

Q = discharge (ft^3/min).

Flow over a trapezoidal weir is given by (Metcalf and Eddy, Inc., 1972):

$$Q = 2/3\ \sqrt{2g}\ L\ H^{3/2} + 8/15\ Z\ \sqrt{2g}\ H^{5/2}$$

where g = gravitational acceleration (32.2 ft/sec^2)

L = length of weir crest (ft)

$H = V^2/2g + h$

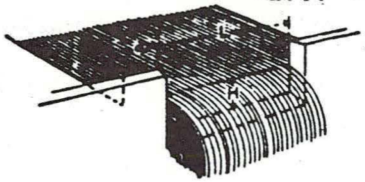
V = flow velocity over weir crest (ft/sec)

h = upstream water surface height above weir crest (ft)

Z = slope of the side contractions.

Flumes - Flumes are advantageous over weirs and chutes because they yield accurate flow measurements and can be portable. Although installation is simple, the following conditions must be met to insure accurate measurements (Albertson et al., 1960):

Table 5.



Discharge From Rectangular Weir with End Contractions

Figures in Table are in Gallons Per Minute

Head (H) in Inches	Length (L) of weir in feet: 1	3	5	Additional g.p.m. for each ft. over 5 ft.	Head (H) in Inches	Length (L) of weir in feet: 3	5	Additional g.p.m. for each ft. over 5 ft.
1	35.4	107.5	179.8	36 05	8	2338	3956	814
1¼	49.5	150.4	250.4	50.4	8¼	2442	4140	850
1½	64.9	197	329 5	66.2	8½	2540	4313	890
1¾	81	248	415	83.5	8¾	2656	4511	929
2	98.5	302	506	102	9	2765	4699	970
2¼	117	361	605	122	9¼	2876	4899	1011
2½	136.2	422	706	143	9½	2985	5098	1051
2¾	157	485	815	165	9¾	3101	5288	1091
3	177 8	552	926	187	10	3216	5490	1136
3¼	199 8	624	1047	211	10½	3480	5940	1230
3½	222	695	1167	236	11	3716	6355	1320
3¾	245	769	1292	261	11½	3960	6780	1410
4	269	846	1424	288	12	4185	7165	1495
4¼	293 6	925	1559	316	12½	4430	7595	1575
4½	318	1006	1696	345	13	4660	8010	1660
4¾	344	1091	1835	374	13½	4950	8510	1780
5	370	1175	1985	405	14	5215	8980	1885
5¼	395.5	1262	2130	434	14½	5475	9440	1985
5½	421.6	1352	2282	465	15	5740	9920	2090
5¾	449	1442	2440	495	15½	6015	10400	2165
6	476.5	1535	2600	528	16	6290	10900	2300
6¼		1632	2760	560	16½	6565	11380	2410
6½		1742	2920	596	17	6925	11970	2520
6¾		1826	3094	630	17½	7140	12410	2640
7		1928	3260	668	18	7410	12900	2745
7¼		2029	3436	701.5	18½	7695	13410	2855
7½		2130	3609	736	19	7980	13940	2970
7¾		2238	3785	774	19½	8280	14460	3090

This table is based on Francis formula:

$Q = 3.33\ (L - 0.2H)\ H^{1.5}$

which

Q = cu. ft. of water flowing per second.

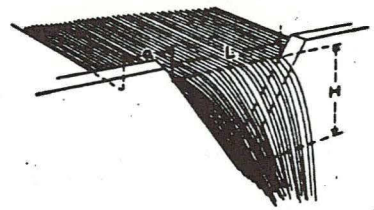
L = length of weir opening in feet. (should be 4 to 8 times H).

H = head on weir in feet (to be measured at least 6 ft. back of weir opening)

a = should be at least 3 H.

Table 6.

Discharge from Triangular Notch Weirs with End Contractions



Head (H) in Inches	Flow in Gallons Per Min.: 90° Notch	60° Notch	Head (H) in Inches	Flow in Gallons Per Min.: 90° Notch	60° Notch	Head (H) in Inches	Flow in Gallons Per Min.: 90° Notch	60° Notch
1	2.19	1.27	6¾	260	150	15	1912	1104
1¼	3.83	2.21	7	284	164	15½	2073	1197
1½	6.05	3.49	7¼	310	179	16	2246	1297
1¾	8.89	5.13	7½	338	195	16½	2426	1401
2	12.4	7.16	7¾	367	212	17	2614	1509
2¼	16.7	9.62	8	397	229	17½	2810	1623
2½	21.7	12.5	8¼	429	248	18	3016	1741
2¾	27.5	15.9	8½	462	267	18½	3229	1864
3	34.2	19.7	8¾	498	287	19	3452	1993
3¼	41.8	24.1	9	533	308	19½	3684	2127
3½	50.3	29.0	9¼	571	330	20	3924	2266
3¾	59.7	34.5	9½	610	352	20½	4174	2410
4	70.2	40.5	9¾	651	376	21	4433	2560
4¼	81 7	47.2	10	694	401	21½	4702	2716
4½	94.2	54.4	10½	784	452	22	4980	2878
4¾	108	62.3	11	880	508	22½	5268	3041
5	123	70.8	11½	984	568	23	4565	3213
5¼	139	80 0	12	1094	632	23½	5878	3391
5½	156	89.9	12½	1212	700	24	6190	3574
5¾	174	100	13	1337	772	24½	6518	3763
6	193	112	13½	1469	848	25	6855	3958
6¼	214	124	14	1609	929			
6½	236	136	14½	1756	1014			

Based on formula:

$Q = (C)\ (4/15)\ (L)\ (H) \sqrt{2gH}$

in which Q = flow of water in cu. ft. per sec.

L = width of notch in ft. at H distance above apex.

H = head of water above apex of notch in ft.

C = constant varying with conditions, .57 being used for this table.

a = should be not less than ¾ L.

For 90° notch the formula becomes

$Q = 2.4381 H^{5/2}$

For 60° notch the formula becomes

$Q = 1.4076 H^{5/2}$

—Courtesy Ingersoll-Rand Co.

a. The flume must be set at the proper elevation in the channel so that backwater or drawdown conditions are not created.

b. The flume must be set in a horizontal position.

c. The flow condition (free or submerged) must be determined in order to calculate discharge.

The following equation may be used to determine discharge through a Parshall flume (see Fig. 2).

$$Q = 4WH_a^{1.522W^{0.026}}$$

where Q = discharge (ft^3/min)

W = throat width (ft)

H_a = head for free flow condition, $H_b/H_a < 0.75$, (ft)

If $H_b/H_a > 0.75$, use $H_a - H_b$ in place of H_a. In addition to the above formula, discharge can be calculated from rating tables supplied with the flume.

Horizontal or Inclined Pipes - This method yields approximate discharge rates from horizontal or inclined pipes flowing full or partially filled. The method is described in Figure 3.

Stream Velocity Measurements - Stream velocity can be used to calculate discharge with the following relation:

$$Q = VA$$

where Q = discharge rate, V = flow velocity, and A = flow area (width x depth). Various velocity measurement techniques are discussed below:

Current meters - The Price current meter is the most widely used velocity meter in the United States. Mean stream velocities are determined by measuring the velocities at the 0.2 and 0.8 flow depths and then averaging. These meters usually yield very accurate results,

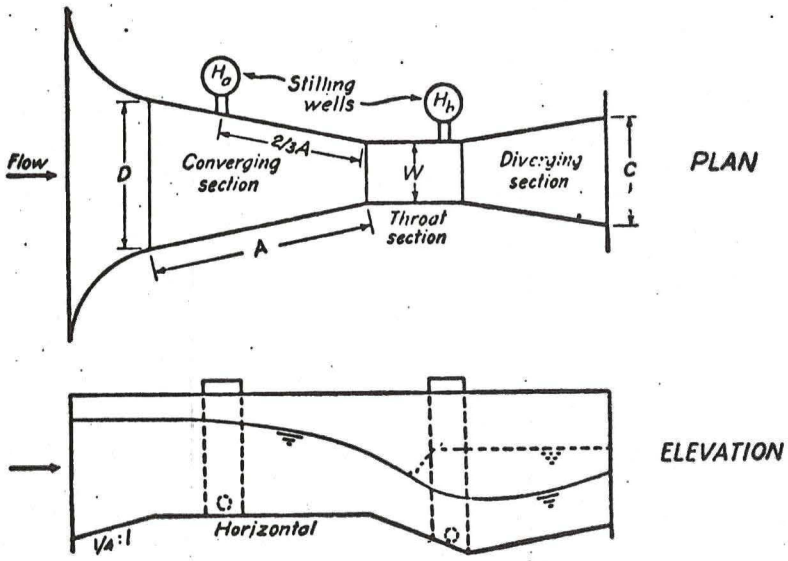
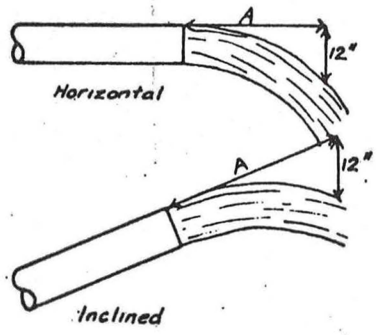


Figure 2. Parshall flume.

(FULL PIPES)



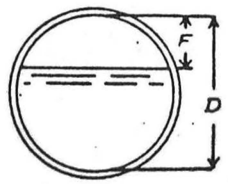
A fairly close determination of the flow from full open pipes may be made by measuring the distance the stream of water travels parallel to the pipe in falling 12 inches vertically.

Measure the inside diameter of the pipe accurately (in inches) and the distance (A) the stream travels in inches parallel to the pipe for a 12-inch vertical drop. (See diagrams)

The flow, in gallons per minute, equals the distance (A) in inches multiplied by a constant K obtained from the following table:

I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K	I.D. Pipe	K
2	3.3	4	13.1	6	29.4	8	52.3	10	81.7	12	118.
1/4	4.1	1/4	14.7	1/4	31.9	1/4	55.6	1/4	85.9	1/2	128.
1/2	5.1	1/2	16.5	1/2	34.5	1/2	59.0	1/2	90.1	13	138.
3/4	6.2	3/4	18.4	3/4	37.2	3/4	62.5	3/4	94.4	1/2	149.
3	7.3	5	20.4	7	40.0	9	66.2	11	98.9	14	160.
1/4	8.6	1/4	22.5	1/4	42.9	1/4	69.9	1/4	103.	1/2	172.
1/2	10.0	1/2	24.7	1/2	45.9	1/2	73.7	1/2	108.	15	184.
3/4	11.5	3/4	27.0	3/4	49.0	3/4	77.7	3/4	113.	16	209.

(PARTIALLY FILLED PIPES)



For partially filled pipes, measure the freeboard (F) and the inside diameter (D) and calculate the ratio of F/D (in percent). Measure the stream as explained above for full pipes and calculate the discharge. The actual discharge will be approximately the value for a full pipe of the same diameter multiplied by the correction factor from the following table:

F/D Percent	Factor	F/D Percent	Factor	F/D Percent	Factor	F/D Percent	Factor
5	0.981	30	0.747	55	0.436	80	0.142
10	.948	35	.688	60	.375	85	.095
15	.905	40	.627	65	.312	90	.052
20	.858	45	.564	70	.253	95	.019
25	.805	50	.500	75	.195	100	.000

—Courtesy U. S. Geological Survey

Figure 3. Estimating flow from horizontal or included pipes.

however excessive debris of fine suspended sediment in the stream may foul the meter.

Floats - Floats are a simple, cheap method of determining flow velocity. The float is placed in the stream and its travel distance vs. time is measured (velocity = distance/time). Oranges and grapefruit are ideal floats because they are highly visible and float just at the water surface so wind effects are minor. This method can only be used in channels with uniform flow free of obstruction or debris.

Velocity head - Discharge or velocity measurements are often times difficult in small channels with shallow flow. In these situations the velocity head method provides reasonable discharge estimates. To determine velocity, a ruler is inserted into the channel such that it is perpendicular to the water surface with the broad side normal to the flow. The difference in water level between the upstream and downstream face of the ruler is inserted into the following equation to determine velocity:

$$V = \sqrt{2gh}$$

where v = velocity (ft/sec), g = gravitational acceleration (32.2 ft/sec^2), and h = difference in water surface elevation between upstream and downstream face of the ruler (ft). With parctice, this method can yield flow estimates within 20% of the actual value.

g. Sediment Discharge Measurement

Measurement of sediment discharge or the sediment load of a stream is a difficult matter which should be left to a competent hydrologist with adequate experience. Briefly, measurement is accomplished through use of samples which accumulate sediment over a measured period of time. Laboratory studies reveal that at least ten sediment samples per station are required to achieve +10% accuracy. The following information is

required to calculate sediment transport rates (Simons and Senturk, 1977):

a. Stream discharge rate.

b. Stream velocity.

c. Cross-sectional flow area.

d. Stream width.

e. Mean sampling depth for suspended sediment.

f. Suspended sediment concentration.

g. Size distribution of channel bed material.

h. Water temperature.

The following conditions must be met in the test reach (Simons and Senturk, 1977):

a. The reach should be uniform in shape and sediment composition.

b. No sharp bends, rills, or excessive vegetation in the test reach.

c. No significant tributaries or diversions should join the river within or immediately above the test reach.

d. The stream bed is composed of sand, no bedrock contacts.

C. Drilling and Sampling Program

1. Designing a Geologic Overburden and Hydrologic Sampling Program

a. General

The goals of any overburden and hydrologic sampling program are to inventory the potential mineral resource and to collect data useful for evaluating the cost of mining and reclamation programs. At the completion of this program, sufficient data must be available to make a final decision concerning a full scale mining operation to extract the mineral resource. Central to these objectives is the conduct of a drilling program which will allow inventory and evaluation of the mineral resources at minimum cost. Data derived from the drilling program will also be

useful in evaluating the physical characteristics of soils and overburden material, ground-water quality and quantity, and reclamation studies. Specifically, answers to the following questions can usually be obtained from the exploration drilling program and a thorough analysis of the core and/or cutting samples:

What is the thickness, depth, and quality of the host rock containing the mineral resource or the coal seam to be mined?

What is the thickness of the overburden above the mineral resource or coal seam, and the interburden between coal seams?

What is the extent, nature, and distribution of various soils within the exploration boundaries?

What are the rock types and the physical and chemical characteristics of the overburden, interburde, and floor material?

What are the stratigraphic relations (lateral continuity or variability) of the various rock units that constitute the overburden material?

What structural features such as joints, faults, and discontinuities are present that might affect subsequent mining operations?

What are the depths of weathering and mechanical breakdown for specified overburden units?

What are the characteristics of the main water-bearing units in the over burden (e.g., their transmissivity, storage coefficients leakage coefficients, ground water flow rates, and water quality)?

What will be the impacts of the mining operation on the ground water system and its users?

b. Drill Hole Spacing and Location

In a recent Environmental Protection Agency report (Smith et al., 1976, p. 5) it was recommended that detailed geologic overburden sampling

of rock columns down to the coal should be required arbitrarily, at intervals of 1 km (0.6 mi) or less, depending on the rate of lateral change in rock strata. Recommendations of this type are most certainly unwarranted for several reasons:

1) The setting of arbitrary limits on drill hole spacing cannot be justified on any basis and will only add to the already high cost of mining operations.

2) Arbitrary limits cannot be justified on the basis of the great variability in the lateral continuity of rock strata in various basins.

If arbitrary limits are unjustified it follows that drill hole spacing and location must be determined uniquely for each geologic province or possibly even for each mine site. In making these determinations several aspects of drilling and sampling theory must be reviewed.

In the first place, it should be emphasized that most programs initiated by mining companies will proceed in a series of stages or phases. Initial drilling may involve only reconnaissance holes with a wide spacing designed to penetrate geologic formations for rock units of potential interest and to provide generalized structural data. If favorable results are forthcoming, additional drilling programs will be designed to locate trends in mineralization. Ultimately, when ore bodies are to be outlined in detail, closely spaced drill holes will be required. This type of exploration program is particularly common in the search for sandstone-type uranium ore bodies. Such a program of successive steps in detecting, outlining, and sampling a disseminated copper-molybdenum sulfide deposit are illustrated in Figure 4. Other types of exploration programs may be more common in coal exploration where the general extent and character of major coal reserves is known with greater certainty. In any event,

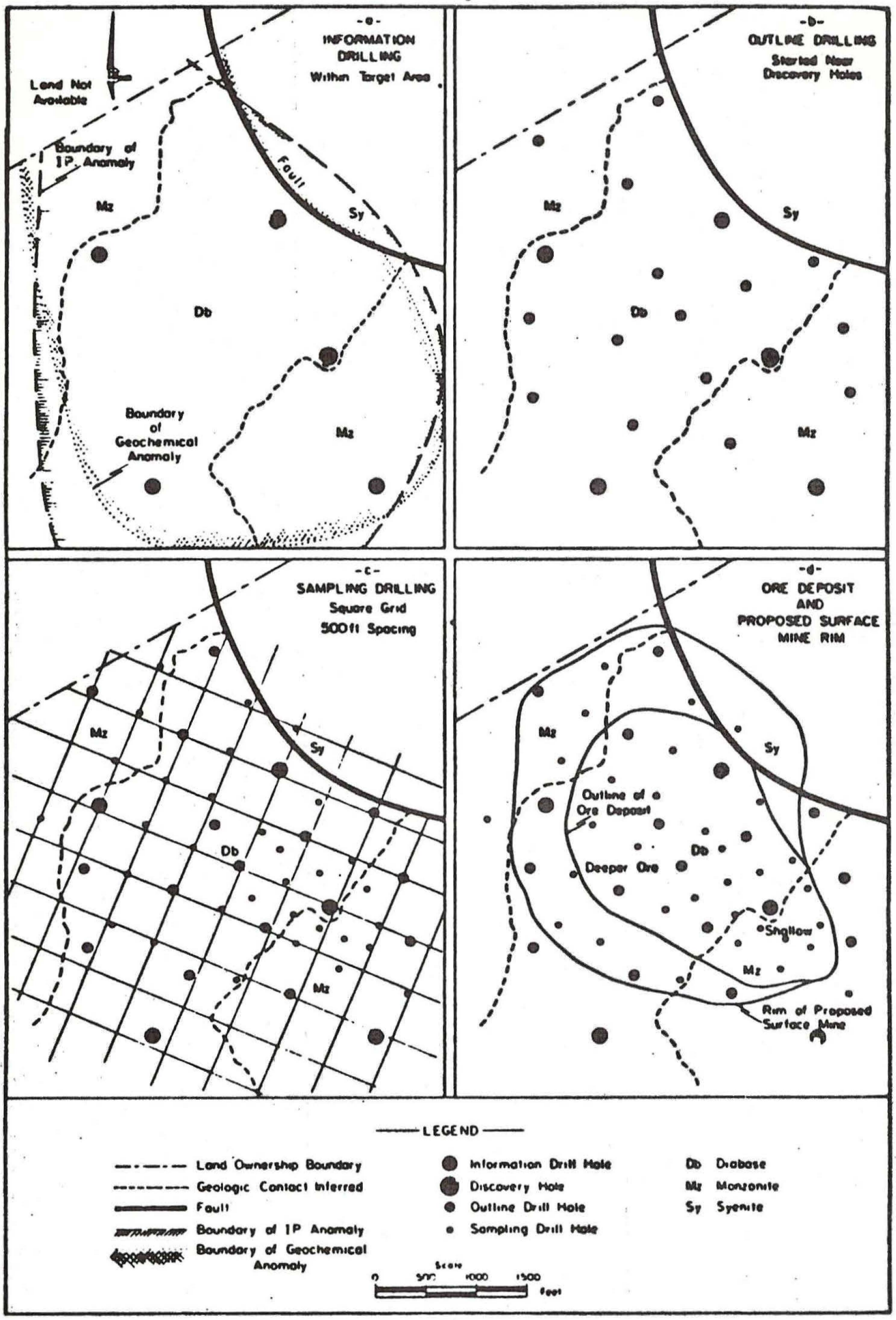


Figure 4. Successive steps in an exploration drilling program to detect, outline, and sample a disseminated copper-molybdenum sulfide deposit (From Peters, 1978, p. 444, after Bailey, P.A., 1968).

modifications to the exploration program will certainly occur as the program progresses and as new data becomes available.

Secondly, one essential element of any sampling design (pattern of drill holes) is a randomization procedure. The notion of random samples disturbs many scientists who feel that samples should be collected on the basis of scientific judgment. In random sampling, however, scientific judgment can be used in defining population to be sampled. Once defined, each potential sample in the population must be given an equal chance of being picked. This can be illustrated by a number of more widely used sampling designs shown in Figure 5.

Assuming the area to be investigated is underlain by homogeneous strata and a simple random sampling plan such as shown in Figure 5A can be used. On the other hand, if the overburden rock strata changes say from sandstones in the northwest to shales and finally to limestones in the southeast portion of the mine area, a stratified random sampling plan (Figure 5B) might be more appropriate. In this case the areas to be samples are selected on the basis of scientific (geologic) judgment while the exact location of each drill hole within an area is selected by some type of random process.

A third consideration involved in the design of a drill hole program involves the type of drilling methods used. The overwhelming majority of holes drilled by mining companies will involve the use of rotary drilling methods which provide cuttings or chips of the overburden units but not continuous cores. Although continuous cores are preferable from the standpoint of detailed evaluation of the overburden, the cost is much greater. A thorough discussion of drilling and sampling methods is found in the following section of this handbook.

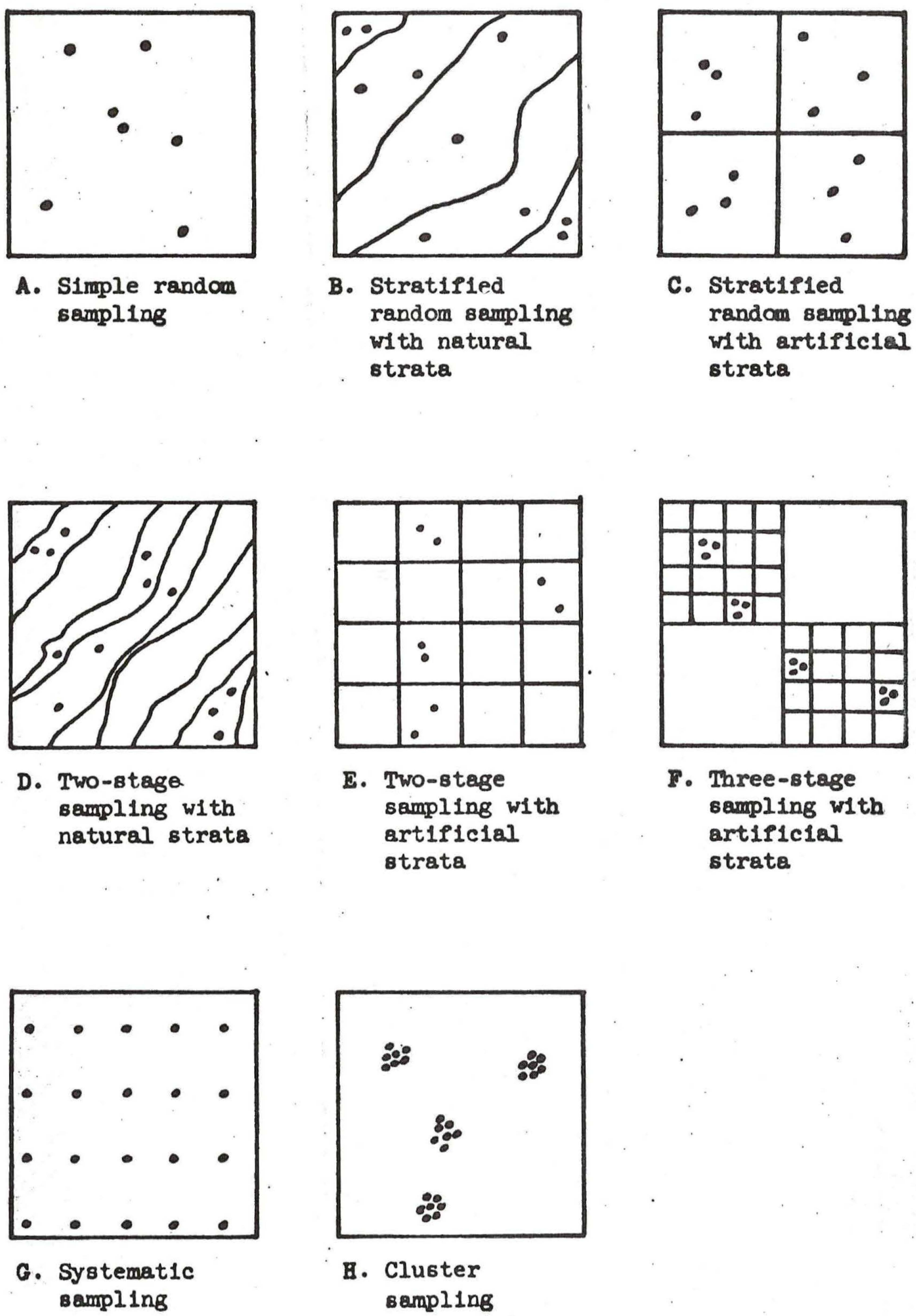


Figure 5. Some of the more commonly used sampling designs. See text for a more complete explanation (after Miesch, 1976, fig. 16, p. 83).

Some continuous cores, along with drill cuttings and geophysical logs from other drill holes should be sufficient for the analysis of the overburden material.

The spacing of continuous cores must therefore be based on specific site considerations (e.g., lateral variability in overburden strata) as determined from studies of cuttings and geophysical logs. Finally, unless other considerations such as the location of water wells, access routes, etc. warrant it, the specific location of continuous core drill holes should be determined by random processes within each area considered to be a geologic population.

c. Sampling Intervals

Smith et al. (1976, p. 5) recommend that routine sequential sampling of overburden columns (from continuous cores) with depth should require at least one sample representing each 0.3 m (1 ft) of overburden from the land surface to the top of each coal to be mined. Furthermore, they suggest that if samples for analysis are taken by a qualified geologist or pedologist, the sample interval can be extended to 1.5 m (5 ft). This type of arbitrary limitation on the distribution of samples for laboratory analyses is as unjustified as an arbitrary spacing of drill holes.

The type, purpose, and amount of sample needed for a particular analysis must be considered in determining sampling intervals. For example, the amount of core material needed for preparing a thin-section for mineralogical determinations is extremely small compared with the amount of sample needed for salinity, fertility, textural analysis, or plant growth studies in the greenhouse. An arbitrary sampling interval of 0.3 m for thin sections would, undoubtedly, produce redundant data, whereas, the same interval would result in insufficient samples to run other desired chemical and physical analyses.

There are at least two logical ways to approach the method of sampling intervals within a continuous core.

1) The geologic overburden can be divided into rock types (sandstone, shale, mudstone, etc.) and each unit can be samples according to the thickness of the strata. This type of procedure is generally satisfactory, however, it may provide unnecessary duplication of analyses of the same rock type if it occurs repeatedly in a core. Age differences between the upper and lower portions of a core may, however, justify this repetition as older strata with the same visual characteristics may have different chemical aspects because of diagenetic alterations (alteration of the rock after deposition and burial).

2) A more satisfactory, but also more complicated method of determining sample intervals, involves the recognition of the paleoenvironments of the over burden (i.e., the equivalent modern environment in which a particular stratum was deposited). Once these paleoenvironments are recognized the strata can be divided into a number of genetically related units (populations), each of which can be sampled for laboratory analyses. The justification of this type of approach can be found in Caruccio et al. (1977, p. 1 and 2). These authors have found that the occurrence of framboidal iron disulfide, for example, within a particular rock strata is a function of its paleoenvironment. That is to say, the conditions under which the rock was deposited control the formation of certain toxic minerals. Thus the association of framboidal pyrite to certain paleoenvironments (rock sequences) in eastern coals is a key to the identification of rocks associated with coal strata which, when mined, will produce acid mine drainage problems.

This second type of sample interval selection shows great promise for use in the future. However, there are several problems associated with the use of this plan at the persent time. Only some geologists and soil scientists have the training to recognize the paleo-environments of overburden strata and the relationships which appear valid for eastern coals are only now being tested on western coal bearing sequences. For example, Moran et al. (1978) in a study of North Dakota lignite bearing sequences suggest that geochemical variations in overburden materials may be related to the enviroment of deposition. Unfortunately they present very little data on correlations to support their statement. The authors of this handbook are currently gathering data from coal bearing sequences in the Powder River Basin to test this contention. However, no conclusions are available at this time.

For these reasons we recommend the first procedure of dividing the overburden strata into rock types on the basis of macroscopic (visual) differences and using these units as sample intervals.

d. Hydrologic Considerations

In order to evaluate the existing groundwater quantity and quality and to determine the impact of mining on the ground water system and its users, a surveillance network must be established that is representative of the system and that provides data concerning the structure, geometry, and hydraulic characteristics of the system. Physically, this surveillance network will consist of a number of monitoring wells, some of which will certainly be used to obtain geologic overburden information as discussed above. With the information obtained from this network it will be possible to estimate the system's response to natural and manmade stresses.

The first and most important step in designing a ground water monitoring network is to identify the purpose and objectives of the monitoring program. Once this is accomplished, the investigator determines the optimum location and number of wells in the network necessary to attain these goals. The following examples illustrate the relationship between the purpose and pattern of two idealized observation networks. For instance, changes in ground water levels and storage volumes are best observed via an array of randomly spaced wells (Figure 5A) where as specific recharge and discharge locations should be monitored by clusters of wells in each area (Figure 5H). In both examples, the number of wells required in the study area depends upon the complexity of the aquifer system and the level of detail desired (Heath, 1976).

The hydrologic characteristics of an aquifer system are largely determined by the areal geologic conditions. The geologic conditions must be incorporated into the design of an observation network if it is to provide accurate information concerning the geometry and hydrologic parameters of the aquifer system. In many areas the detailed subsurface geology is not known prior to drilling, thus the monitor network must be flexible so that it may be modified as additional data is obtained during drilling. Potential drilling costs may be reduced in situations where geologic formations provide information about subsurface conditions. The investigator should not be overly reliant on surface relations, however, in many areas the conditions at depth are totally unrelated to the topography and geology at the surface.

At this point it is useful to examine qualitatively, the various types of geologic material and structures with respect to their aquifer characteristics and impacts on the monitor network design.

<u>Unconsolidated formations</u> - Unconsolidated aquifer materials are composed of sand and gravel zones usually associated with silt and clay. These sediments exhibit intergranular permeability and water contained in them exists in pore spaces or the interstices between grains. Gravel and sand deposits occur naturally in a variety of configurations; extensive, continuous thick or thin beds, discontinuous beds and lenses, stringers and erosion channels.

Monitoring network design is fairly straightforward in extensive continuous deposits; an array of randomly spaced wells penetrating the same aquifer is sufficient. Discontinuous beds, lenses, and erosion channels are a difficult monitoring problem requiring a detailed knowledge of the subsurface geology. In this case, well spacing is dependent upon the variability of the aquifer deposits; highly variable, discontinuous formations require a greater monitor well density than continuous deposits. Monitor networks in channelized aquifer deposits should consist of wells placed at regularly-spaced intervals along the channel axis. A detailed monitor network in these deposits would require an extensive drilling program at great expense.

<u>Consolidated formations</u> - Consolidated aquifer formations are composed of sandstones exhibiting intergranular and/or fracture permeability or other rock types with fracture or solution channel permeability. Continuous sandstone units with intergranular permeability can be monitored by a network of randomly spaced wells penetrating the same formation. Aquifers with fracture or solution channel permeability may be more difficult depending upon the fracture of solution channel density. Highly fractured formations may be considered as homogeneous systems on a large scale and monitored accordingly. Aquifer systems with widely spaced

fractures or solution channels require extensive subsurface exploration before a representative monitoring network can be established.

Geologic structure - For our purpose, geologic structure includes such features as faults, folds and bedrock contacts.

Faults may be barriers or conduits for ground water movement depending upon the lithology and geologic history of the region. Faults frequently become ground water barriers due to the formation of impermeable clay gouge zones or by offsetting the aquifer formation until it abuts impermeable deposits. Faults can be ground water conduits when permeable fracture zones are created in otherwise impermeable materials.

Folds have various effects on the ground water flow regime depending upon the type of strata involved and the fold intensity. Localized, discontinuous, perched, and compartmentalized ground water bodies commonly occur in areas of complex geologic structure (Bean, 1967).

Ideally a monitoring system should have wells above and below the aquifer in addition to those within the aquifer in order to gain information about the three-dimensional response of the aquifer system to stresses (Heath, 1976). The hydrologist must use the disciplines of engineering, geology, hydrology and economics when designing a monitoring network. In addition, a compromise must be made between the detail produced by the monitor network and its costs.

2. Drilling and Sampling Methods

a. Drilling

This section mentions the most common methods for drilling, but no attempt has been made to describe the procedure for drilling. Drilling techniques and equipment are described in detail by Acker (1974), Campbell and Lehr (1973), and Johnson (1975). Table 7 summarizes various drilling

Table 7. Summary of Commonly Used Drilling Methods

Method	Recommended Overburden Conditions	Overburden Sampling And Formation Logging	Water Yield and Quality Tests
Cable-Tool Percussion	Good for fractured or broken formations.	Undisturbed cores cannot be obtained; cutting samples are of sufficient size to permit geological identification and description; samples are not contaminated with drilling mud; samples bailed from each interval represent about a 3 to 5 foot zone; when casing is used during drilling there is little chance of sample contamination for caving.	Water bearing zones can be easily identified; there is a minimum contamination of water producing zones; potential aquifers can be tested for yield and quality of water by bailing or pumping; permits measurement of static water levels.
Rotary Drilling (Direct Circulation) using water or drilling mud as the drilling medium.	Unsatisfactory or difficult in loose, coarse-grained overburden with cobbles or boulders.	Drill cuttings are mixed from different depths and contaminated by drilling mud when used; cuttings brought to the surface can vary with depth characteristics rather than from where the material was penetrated; sample lag time in deeper holes can become troublesome in obtaining a reliable geologic log.	Measuring static water levels, taking representative water samples, and performing pump tests of individual aquifers is not practical; when used for drilling water wells the holes should be drilled using water or drilling additives that are biodegradable so that the drilling medium can be removed from the well during development.
Rotary Drilling (Direct Circulation) using air as the drilling medium.	Recommended for highly fractured or cavernous rock such as coal or limestone where conventional rotary drilling would result in the loss of drilling fluids and circulation.	Instant cuttings recovery; as-is moisture samples; no washed cores; samples are not contaminated with drilling mud.	Depth to water table can be determined; there is a minimum contamination of water producing zones.
Air-Percussion Rotary Drilling	Best for consolidated rock formations.	Samples are not contaminated with drilling mud.	Depth to water table can be determined; there is a minimum of contamination of water producing zones.
Reverse Circulation Rotary Drilling	Recommended for drilling large holes in unconsolidated formations such as sand, silt, or soft clay.		
Rotary Drilling with Reverse Circulation and Dual Wall Pipe	Excellent for drilling and sampling in formations which are highly fractured and/or have voids and cavities.	Produces larger sized chip particles than that of conventional rotary equipment; more accurate and more continuous samples compared to other rotary methods; eliminates sample contamination caused by caving formations or particles eroded from the sides of the hole.	Water aquifers can be identified immediately when drilling with air; permits measurement of static water levels.
Hammer Drilling with Reverse Circulation and Dual Wall Pipe	Designed to penetrate alluvial formations, and can penetrate sand, gravel, and boulder formations at rapid speed.	Provides a continuous and accurate geological sample of the penetrated material; no critical layers such as soft seams, organic layers, etc., are missed; large cobbles can be lifted without prior crushing.	Aquifers can be pinpointed within inches because once the drive bit has progressed beyond the aquifer, the samples become dry again.
Auger Boring	This method is best suited for loose, dry, moderately cohesive soils and broken formations which will not easily cave.	Obtains representative disturbed samples; generally not satisfactory for obtaining samples below the water table.	Water samples are not contaminated with any drilling medium; permits measurement of static water levels.
Drive-Tube Boring	Not satisfactory in coarser fine grained soils, clean sands, or cohesionless soils below the water table.	Obtains representative disturbed samples.	Water samples are not contaminated with any drilling medium; permits measurement of static water levels.
Wash Boring	Slow in hard or cemented layers.	Representative samples cannot be obtained.	
Jetting	Slow in hard cohesive soils.	No information for formation logging or samples for classification.	

methods that affect overburden sampling and formation logging; and their affect upon water yield and quality tests. Some recommended drilling methods for various types of geologic overburden are also given in the table.

b. Sampling During Drilling

Three methods to advance samples during drilling are driving, augering, and rotary core drilling. Drive sampling is used for surficial materials (soils) both above and below the water table. Hammering, jacking, pushing, single blow, and shooting are used to drive samplers into the soil. Rapid continuous pushing using drill rods and the hydraulic cylinders of a drill rig is recommended for overburden studies.

Auger sampling is used in surficial materials (sands, silts, clays) above the water table. Hollow stem augers permit sampling below the water table. This method advances the hole with a hollow stem auger, when sampling is desired the drilling is halted and a drive sampler is passed through the hollow stem to take samples at the bottom of the auger stem. A rotary drill rig can be fitted for auger drilling.

Rotary core drilling can be used to obtain rock and soil samples. Rotary core drilling is more costly and complicated than drive sampling or augering techniques. More variables must be considered for rotary coring such as coring bits and circulation of a drilling medium such as air, water, or mud.

c. Using Drilling Fluids During Sampling

During rotary drilling it is necessary to use a drilling medium such as air, water, or mud for lifting cuttings from the borehole. For overburden studies it is recommended that air be used where possible. The next recommended choice would be water.

The use of drilling mud should be avoided unless absolutely necessary to overcome lost circulation problems, or to lift cuttings from deep holes, or to support the borehole during drilling. When using mud additives it is recommended that a biodegradable mud be used if the borehole is to be converted into a water well.

Rock cores obtained when using drilling mud should be carefully washed before any chemical tests are completed on samples. A chemical analysis should be obtained on the water and/or drilling mud when used. This analysis will be useful when interpreting any chemical tests that might be done on soil or rock samples. Table 8 shows how various drilling mediums can affect chemical tests.

d. Prevention of Borehole Caving During Sampling

During drilling and sampling in soft or cohesionless material the walls and bottom of the borehole can cave. The sides of the borehole can gradually squeeze in if the soil or rock is plastic such as clay material. Casing the borehole with pipe or the use of drilling mud can prevent caving or squeezing in of the borehole.

For overburden studies it is recommended that the borehole be cased with pipe when drilling materials that can cave or squeeze in. As drilling progresses the drill hole is lined with pipe having an inside diameter which permits the passage of the drill bit to advance the hole and for entry of the sampler. When drilling with rotary systems the use of drilling mud for supporting the sides of the borehole should be avoided unless absolutely necessary. This will prevent contamination of chemical tests and water aquifers.

e. Sampling and Rotary Coring Bits

There are a wide variety of coring bits available to drill various

Table 8. Effects of Sampling Methods on Results of Chemical Analysis of Overburden Samples (adapted from Power and Sandoval, 1976)

Drilling Methods	Positive Aspects	Negative Aspects
1. Pneumatic drilling (air), no solutions used, and cuttings blown out of drill hole by compressed air. Samples taken in 1 foot intervals.	Least contaminated, fastest, least expensive	Solid core was not obtained; difficult to drill when overburden is wet.
2. Coring by circulating water through the drill stem. (Low salt)	Less contamination than with high salt but greater than using Revert.	Lost circulation, soluble salts leached from near surface zone, high cost.
3. Coring by circulating bentonite drilling mud and water through the drill stem. (mud)		Lost circulation, soluble salts leached from near surface zone, high cost.
4. Coring by circulating water with added sodium and magnesium sulfate through the drill stem. (High salt)		Lost circulation, greater contamination than with low salt, soluble salts leached from near surface zone, high cost.
5. Coring by circulating an organic polymer (Revert) and water through the drill stem.	Circulation was not lost during drilling.	High cost.
6. Highwall samples (used as reference samples)		

geologic materials. Tungsten carbide insert and sawtooth bits are often used in soils and soft or medium hard rocks because they are less expensive than diamond bits. Diamond bits can be used in soft and medium hard rocks, and are a necessity in hard rocks. Table 9 gives some recommended coring bit designs to be used for various geologic conditions.

f. Suggested Techniques to Obtain a High Percentage of Core Recovery in Soft or Poorly Consolidated Materials

Good core recovery depends a great deal upon the skill of the drillers who are working with the coring job. The following suggestions can help improve core recovery when used by drillers:

1. Keep the weight on the bit low to prevent plugging the ports of the bit, and to prevent core breakage.

2. Use a high rotation speed.

3. Use a face-discharge bit or a pilot bit with narrow kerf.

4. Use a high viscosity drilling mud.

5. Take large sized cores. In general, the larger the core size taken the better the recovery.

6. Keep trash and lost circulation materials out of the drilling water or mud.

g. Sampling and Coring Techniques

The sampling and coring techniques mentioned in this handbook can be grouped into the following categories: 1) drive samplers, 2) auger samples, 3) rotary coring samples, 4) special techniques. Table 10 gives some guidelines that can be used when selecting a sampling technique for soils or rock overburden.

Table 9. Recommended Coring Bit Designs (Acker, 1974)

Geologic Condition	Recommended Bit Design for Best Results	Core Diameter
SOFT		
Calcite	Pyramid Carbide	7/8 to 6 inches
Chalk	Sawtooth	7/8 to 6 inches
Gypsum	Diamond-Pilot Crown	7/8 to 3 11/32 inches
Limestone	Diamond-Large Diameter Conventional Crown	2 3/4 to 6 inches
Talc		
Shale	Diamond-Face Discharge	1 1/8 to 2 5/8 inches
MEDIUM		
Claystone	Pyramid Carbide	7/8 to 6 inches
Siltstone	Diamond-Pilot Crown	7/8 to 3 11/32 inches
Sandstone	Diamond-Conventional Crown	7/8 to 6 inches
Limestone	Diamond-Face Discharge	1 1/8 to 2 5/8 inches
Slate		
Coal		
HARD		
Marble	Diamond-Stepped Crown	7/8 to 3 11/32 inches
Limestone	Impregnated Diamonds - Conventional Crown	7/8 to 3 11/32 inches
Chert		
Garnet Schist		
Granite		
Gneiss		
Garnet Mica		
Dolomite		
Quartzite		
Taconite		
Jasper		

Table 10. Summary of Sampling Techniques for Soils and Geologic Overburden

Sampling Technique	Recommended Geologic Conditions for Best Results	Method of Penetration	Length of Sample Held in Barrel	Core Diameter	Water Table Influence	Core Quality	State of Development	Source*
"Pocket" Solid Barrel Sampler (Spoon Type)	Gravels, sands.	Rotate	36 to 60 inches	1 1/2 to 2 1/2 in.	Recovery and quality of sample questionable below.	Not core sample; disturbed material	Readily available	Longyear, Joy
"Door" or "Window" type sampler	Gravels, sands.	Rotate	36 in.	5 inches	Recovery and quality of sample questionable below.	Not core sample; disturbed material.	Readily available	Joy
Sidewall Sampler	Used only when other sampler types fail	Rotate		1 1/2 to 2 1/2 in.	Recovery and quality of sample questionable below.	Not core sample; disturbed material	Readily available	Joy
Thin Wall "Shelby Tube" Sampler	Silts, clays	Press	24 to 54 inches	1 7/8 to 4 7/8 in.	Satisfactory below with normal care.	Undisturbed core sample	Readily available	Acker, Joy, Longyear, Mobil Drill, Penn Drill, Soil Test, Sprague and Henwood
Solid Barrel Sampler	Sands, silts, clays	Drive or Press	60 in.	1 1/2 to 3 inches	Recovery and quality of sample questionable below.	Disturbed core sample	Readily available	Joy, Longyear
Split Barrel Sampler	Sands, silts, clays	Drive or Press	12 to 24 inches	1 1/2 to 3 inches	Recovery and quality of sample questionable below.	Disturbed core sample	Readily available	Joy, Longyear
Split Barrel Sampler with Liner	Plastic soils	Drive or Press	12 to 24 inches	1 7/16 to 2 15/16 inches	Sample recovery and quality questionable below.	Disturbed core sample	Readily available	Joy, Longyear
Split Barrel Sampler "Maine Type"	Sands, silts, clays	Drive or Press	16 inches	3 1/2 to 5 inches	Sample recovery and quality questionable below.	Disturbed core sample	Readily available	Joy, Longyear
Double Tube Continuous Drive Sampler	Sands, silts, clays	Drive	60 inches	2 7/8 in.	Sample recovery and quality questionable below.	Not core sample; disturbed material	Commercially available on special order	Penndrill
M.I.T. Sampler with retainer and Piano wire	Clays	Drive	30 inches	5 inches	Satisfactory below with normal care.	Undisturbed core sample	Commercially available on special order	Sprague and Henwood
Square Tube Sampler	Clays	Drive	24 inches	2x2 in. square	Satisfactory below with normal care.	Undisturbed core sample	Operational but user fabricated	Wilson (1969)
Wit Sampler with Membrane Retainer	Sands, silts, clays	Drive	12 inches	2 1/2 in.	Relatively trouble free below.	Undisturbed core sample	Research and Development	Wit (1962)
Delft Mud Sampler	Sands, silts, clays	Drive	2 inches	30 to 60 feet	Relatively trouble free below.	Disturbed core sample	Research and Development	Begemann (1961)
Fixed Piston, Thin-Walled Sampler (Hvorslev Type)	Sands, silts, clays	Drive	36 inches	3 to 5 inches	Relatively trouble free below.	Undisturbed core sample	Operational but user fabricated	Mathews (1969)
Free Piston Sampler	Silts, clays	Drive	24 to 30 inches	2 1/2 to 2 7/8 in.	Relatively trouble free below.	Disturbed core sample	Commercially available on special order	Mobile Drill
Hydraulic Fixed Piston Thin-Walled (Osterberg Type)	Sands, silts, clays	Drive	48 inches	2 3/8 to 4 7/8 in.	Relatively trouble free below.	Undisturbed core sample	Readily available	Soiltest
Retractable Plug Sampler	Sands, silts, clays	Drive	6 inches	7/8 inch	Relatively trouble free below.	Not core sample; disturbed material	Readily available	Acker, Mibile Drill, Soiltest, Sprague and Henwood
Stationary Piston Sampler	Sands, silts, clays	Drive	24 to 54 inches	1 7/8 to 4 7/8 in.	Relatively trouble free below.	Undisturbed core sample	Readily available	Acker, Penndrill, Soiltest, Sprague and Henwood

*Sources listed without a date are Manufacturers or Distributors. Addresses for these manufacturers are given in Appendix IV.

Table 10. continued

Sampling Technique	Recommended Geologic Conditions for Best Results	Method of Penetration	Length of Sample Held in Barrel	Core Diameter	Water Table Influence	Core Quality	State of Development	Source*
Stationary Piston Sampler with Liner (Lowe-Acker)	Silts, clays	Drive	6 to 9 inches	2 3/16 in.	Relatively trouble free below.	Undisturbed core sample	Commercially available on special order	Acker
Delft Foil Sampler	Clays, sands	Push	36 in.	2 1/2 in.	Relatively trouble free below.	Undisturbed core sample	Research and Development	Begemann (1961,1971, 1974)
Foil Sampler with Rotary Coring Bit	Sands, silts, clays	Rotate	Up to 36 feet	2 11/16 inches	Satisfactory below with normal care.	Undisturbed core sample	Research and Development	Broms and Hallen (1971), Fukuoka (1969)
Swedish Foil Sampler	Sands, silts, clays	Push	Up to 70 feet	2 11/16 inches	Relatively trouble free below.	Undisturbed core sample	Commercially available on special order	Sprague and Henwood
Double-Tube Auger	Silts, clays	Rotate	46 inches	1 1/4 to 2 1/4 in.	Not suitable below water table.	Undisturbed core sample	Readily available	Soiltest
Shrouded Auger	Sands, silts, clays	Rotate	53 inches	4 1/8 in.	Satisfactory below with normal care.	Not core sample; disturbed material	Readily available	Mobile Drill
Open Spindle Hollow Stem Auger (Moss Technique)	Silts, clays, sands, gravel	Rotate & Drive Combination	Variable	Up to 5 1/2 in.	Satisfactory below with normal care.	Disturbed core sample	Readily available	Mobile Drill
Rubber Sleeved Double Tube Core Barrel	Weakly cemented rock; interbedded hard & soft rock; fractured rock; weak rock.	Rotate	20 to 30 feet	3 inches	Relatively trouble free below.	Core sample	Commercially available on special order	Christensen
Denison Type Sampler	Sands, silts, clays, weakly cemented rock	Rotate	24 to 60 inches	2 3/8 to 6 5/16 in.	Relatively trouble free below.	Undisturbed core sample	Readily available	Acker, Soiltest, Sprague and Henwood
Pitcher Sampler	Sands, silts, clays, weakly cemented rock; interbedded hard & soft rock	Rotate	36 inches	3 to 6 inches	Satisfactory below with normal care	Undisturbed core sample	Readily available	Pitcher Drilling Co.
Large Diameter Swivel Type Core Barrel, Core Lifter in inner barrel	Weakly cemented rock, interbedded hard & soft rock, fractured rock	Rotate	60 to 240 inches	2 1/8 to 5 15/16 inches	Satisfactory below with normal care.	Core sample	Readily available	Acker, Christensen, Longyear, Sprague and Henwood
Swivel Type Core Barrel, core lifter in inner barrel (M-Design)	Interbedded hard & soft rock, jointed rock	Rotate	60 to 240 inches	7/8 to 2 13/16 inches	Satisfactory below with normal care.	Core sample	Readily available	Acker, Christensen, Longyear, Penndrill, Soiltest
Swivel Type Core Barrel, Core Lifter in outer barrel (X-Design)	Jointed rock	Rotate	60 to 240 inches	7/8 to 2 1/8 in.	Satisfactory below with normal care.	Core sample	Readily available	Acker, Longyear, Penndrill, Sprague and Henwood
Swivel Type Core Barrel, Retractable Triple Tube (Australian Design)	Weakly cemented rock, interbedded hard & soft rock, strongly fractured rock	Rotate	60 to 120 inches	1 1/8 to 3 inches	Satisfactory below with normal care.	Core sample	Readily available	Triefus Industries, Odgers Drilling
Wireline, Double Tube Core Barrel	Weak rock, jointed rock	Rotate	60 to 180 inches	1 1/16 to 3 11/32 inches	Satisfactory below with normal care.	Core sample	Readily available	Sprague & Henwoos, Acker, Boyle Bros, Christensen, Longyear, Reed, Reese
Wireline, Double Tube Core Barrel with liner	Weakly cemented rock, interbedded hard & soft rock, fractured rock, weak rock, jointed rock	Rotate	60 to 180 inches	1 5/16 to 3 1/4 in.	Satisfactory below with normal care.	Core sample	Readily available	Longyear
Orienting Double Tube Core Barrel	Interbedded hard & soft rock, weak rock, jointed rock	Rotate	60 to 120 inches	1 5/8 to 5 7/8 in.	Satisfactory below with normal care.	Core sample	Readily available	Christensen
Bishop Sand Sampler	Sand	Push	15 inches	2 3/8 in.	Relatively trouble free below.	Undisturbed core sample	Operational but user fabricated	Serota & Jennings (1957), Bishop (1948)

3. Well Completion Methods

a. Well Construction

Wells can be drilled using any drilling method described in this handbook. The drilling and construction of wells are described in detail by Anderson (1967), Campbell and Lehr (1973), and Johnson (1975).

b. Well Casing

The size, weight, and resistance to corrosion of casing should be considered in water well design. Four inch diameter wells are the smallest size that will handle a submersible pump. Carbon steel casing is highly resistant to soil corrosion, and stainless steel has excellent durability. Plastic casing is used frequently because it is less costly than steel. Polyvinyl chloride (PVC) is used for depths up to 200 feet. Rubber-modified polystyrene is used for depths up to 300 feet. Fiberglass-reinforced epoxy pipe has been used for depths up to 300 feet. Plastic well casings are usually not larger than 6 inches in diameter.

c. Well Screen and Perforated Casing

Wells in unconsolidated materials need openings in the casing to permit entrance of water into the well. In solid rock formations the casing can be left open at the bottom, and water can enter the well through the end of the casing. Well casing can be perforated in the field using, torches, saws, or drills. Casing can also be purchased with perforations that were made at the factory.

Well screens are often used in place of perforated casing. Screen can be purchased with open areas ranging from 2 to 60 percent. Well screens are made of iron, brass, stainless steel, fiberglass, and plastic. The size of perforations, slots, or screen openings are chosen after the particle size distribution of water-bearing zones are determined from

samples taken during drilling.

d. Gravel Packing

Often a drill hole is larger than the outside diameter of the casing so a gravel pack is used to stabilize the formation. The annular space around the well screen or perforations is gravel packed to prevent materials above the water table from caving or slumping into the water producing zone. Gravel packing is also used in unconsolidated formations of fine uniform sand or layered deposits.

Screen openings or perforations are chosen so that 90 percent or more of the gravel pack material will be retained. It is recommended that a gravel pack be 3 to 8 inches thick. The gravel pack material should be clean, well-rounded, quartz grains.

e. Well Sealing

Often it is necessary to protect a water producing zone from contamination by water from other aquifers or from the surface by grouting the well. Grouting is accomplished by filling the annular space around the casing with a slurry of Portland cement, bentonite, perlite, Gilsonite, diatomaceous earth, or other materials.

f. Well Development

Well development after drilling and casing accomplshes the following: 1) clays, silts, and fine sands are removed from around the aquifer and well; 2) the porosity and permeability of the formation is increased; 3) material around the screens or perforations is stabilized so that the well yields sand-free water; 4) clogging and compaction of the formation which occurs during drilling is corrected. Table 11 lists the commonly used methods for developing wells.

Table 11. Methods for Developing Water Wells

Method	Advantages	Disadvantages
Over-Pumping	Convenient method for small wells or poor aquifers.	Not adequate for large wells; will not develop maximum efficiency in a well; tends to cause sand to "bridge" in the formation; requires the use of high capacity pumping equipment
Back-Washing	Can effectively reduce "bridging".	Fine sand, mud, silt, or clay can be washed into the well from the formation; not effective unless combined with surging, bailing, or pumping; large quantities of water required.
Surge-Plungers	Low cost; convenient to use for Cable-Tool rigs.	Can produce unsatisfactory results when an aquifer contains clay because the casing or screen can collapse if it becomes plugged with mud; sometimes the well seal can be disturbed when surging.
Compressed Air	Rapid method.	Where yield is very weak and drawdown rapid, or submergance is low, other methods will be more satisfactory.
High Velocity Jet	Most effective method; simple to apply.	
Blasting	Rapid method.	Used for solid rock wells only.
Acidizing	Rapid method.	Used for limestone aquifers only.

4. Geophysical Logging Methods

Well logging is the recording of various geophysical properties of the strata (formations) penetrated by a drill hole. Logging operations are performed by lowering measuring probes or "sondes" into a drill hole on an insulated cable. The measurements are recorded at the surface as the sonde is pulled out of the hole. The recording device at the surface produces a graph of the borehole versus the depth of penetration (Fig. 6). Depending upon the nature of the soned, a number of geophysical properties of the geologic strata and contained fluids including electrical, radioactive, and acoustical can be measured.

Down-hole geophysical logging methods are well established techniques in the petroleum industry for use in identifying potential reservoir rocks and for determining their porosity and permeability and the nature of fluids present. From the standpoint of overburden analysis an equally important aspect is the ability to identify rock units and to correlate these units between wells. Particular rock formations may yield log curves with distinctive patterns (Figs. 6 and 7) making it possible to correlate not only major lithologic (rock type) breaks, but many points within the formations themselves (Telford et al., 1976, p. 772). Much of the up to date methodologies on advancements in downhole geological logging are found in petroleum related literature. Geophysical logs have been run on a routine basis for years in the petroleum industry and are now being run on a more routine basis than in the past in mining exploration. They hold a great potential for providing geochemical, geotechnical, and assay data from non-cored drill holes. The best results are obtained when geophysical logs can be calibrated against core from a cored hole (Dames and Moore, 1975, Vol. II, p. 92). Principles of

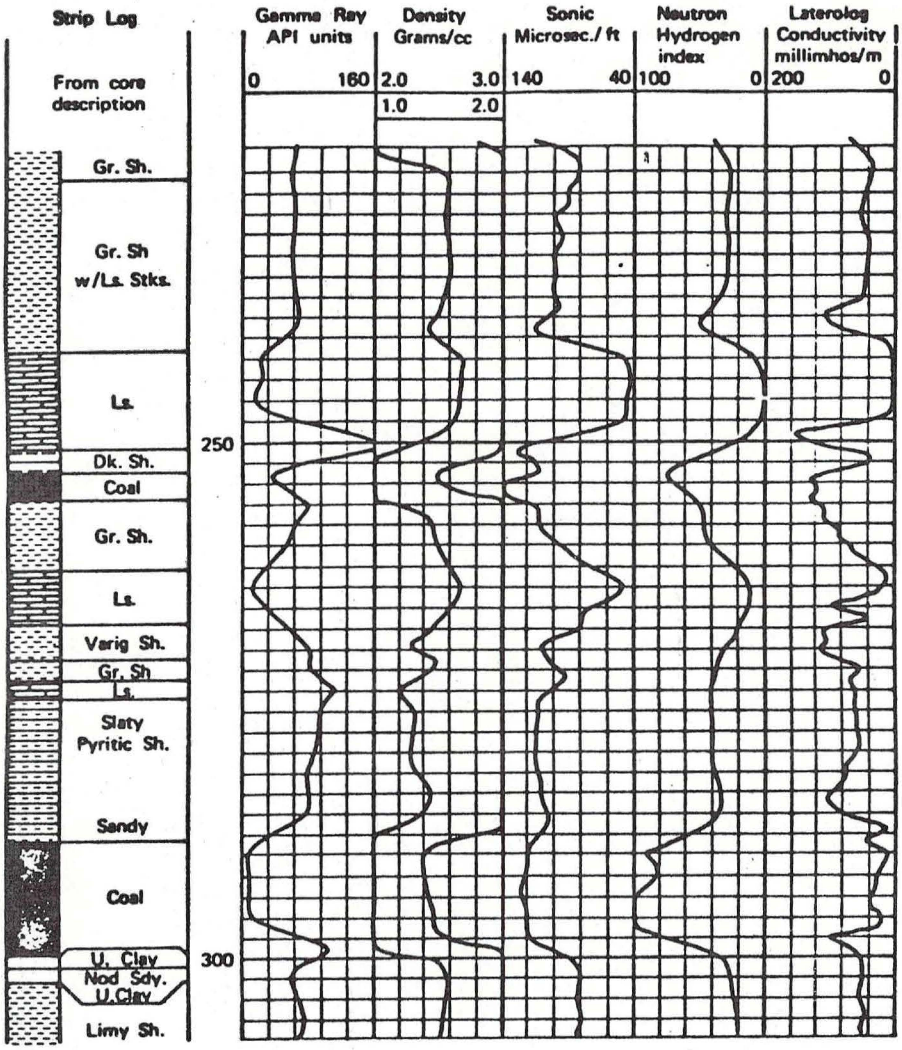


Figure 6. Geophysical log curves from a coal field exploration drill hole showing correlation between various rock types and log shapes (From Peters, 1978, p. 453, after Jenkins, 1969).

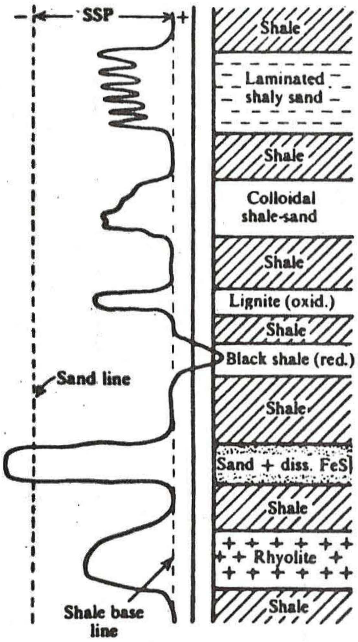


Figure 7A. Characteristics of SP curves for various rock units (after Telford, et al., 1976, p. 785).

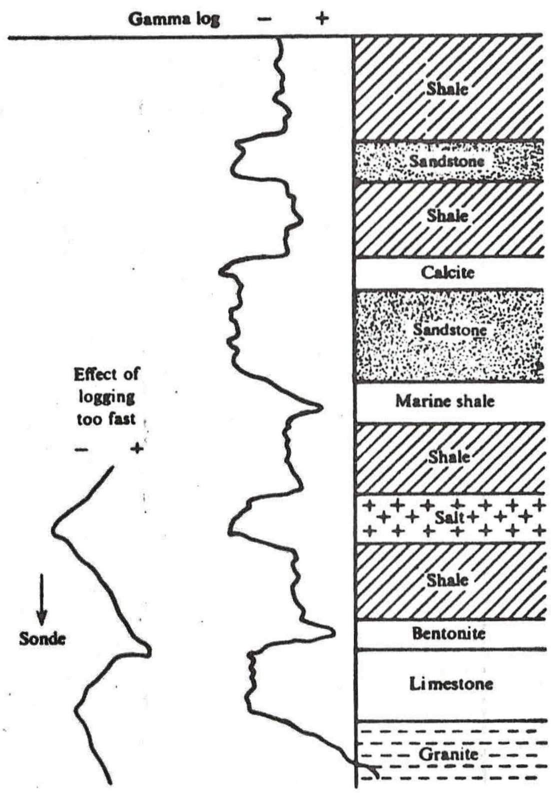


Figure 7B. Typical gamma ray log curve for various rock units (after Telford, et al., 1976, p. 793).

geophysical well logging are discussed in Chapter 11 of Telford et al. (1977) and in Chapter 13 of LeRoy et al. (1977). The various methods of downhole geophysical logs commonly used in the evaluation of mineral deposits are reviewed by Scott and Tibbetts (1974). Bond et al. (1971) discuss the various well logging techniques used in the coal mining industry and Tixler and Alger (1970) discuss the geophysical log evaluation of nonmetallic mineral deposits. Table 12 modified from Dames and Moore (1976) presents a list of the more common geophysical logging techniques along with their uses and recommended conditions.

5. <u>Subsurface Hydrologic Measurements</u>

The purpose of subsurface hydrologic measurements is to provide information sufficient to determine the quantity of groundwater, direction and magnitude of groundwater flow, recharge, and the relationship between ground and surface waters. The configuration of the piezometric surface or water table, hydraulic conductivity, transmissivity, and storage characteristics of each aquifer system are required. Piezometric surface and water table data are determined from static ground water elevation measurements and the hydraulic coefficients are determined from the observation of the time rate of change of groundwater elevation during aquifer tests.

a. <u>Water Surface Elevation Measurements</u>

A permanent reference point, from which all depth-to-water measurements are made, should be established at each well. A notch in the well casing or other indication of a particular reference point will suffice. The elevation of each reference point (measuring point) is established relative to a common datum (preferably mean sea level) with an accuracy of at least 0.1 ft. The depth to water from the reference point is

Table 12. Standard down-hole geophysical logging methods (modified after Dames and Moore, Vol. II, 1976, p. II-94 and II-95)

METHOD	USES	RECOMMENDED CONDITIONS
ELECTRIC LOGGING:		
Single electrode resistance	Determining depth and thickness of thin beds. Identification of rocks, provided general lithologic information is available. Correlation of geologic formations or beds. Determining casing depths.	Fluid-filled uncased hole. Fresh mud required. Hole diameter less than 8 to 10".
Short normal (electrode spacing of 16")	Picking tops of resistive beds. Determining resistivity of the invaded zone. Estimating porosity of formations (deeply invaded and thick interval). Correlation and identification of geologic formations provided general lithologic information is available.	Fluid-filled uncased hole. Ratio of mud resistivity to formation - water resistivity should be 0.2 to 4.
Deep lateral (electrode spacing approx. 19")	Determining true resistivity where mud invasion is relatively deep. Locating thin beds.	Fluid-filled uncased hole. Fresh mud. Formations (rock units) should be of thickness different than electrode spacing and should be free of thin limestone beds.
Limestone sonde (electrode spacing of 32")	Detecting permeable zones and determining porosity in hard rock. Determining formation factor in sites.	Fluid-filled uncased holes. May be salty mud. Uniform hole size. Beds thicker than 5 feet.
Laterlog	Investigating true resistivity of thin beds. Used in hard formations drilled with very salty muds. Correlation of formations, especially in hard rock regions.	Fluid-filled uncased holes. Salty mud satisfactory. Mud invasion not too deep.
Neutron	Delineating formations and correlation in dry or in cased holes. Qualitative determination of shales, tight formations, and porous sections in cased wells. Determining porosity and water content of formations, especially those of low porosity. Distinguishing between water or oil-filled or gas-filled reservoirs. Combined with gamma-ray log for better determination of lithology (rock type) and correlation of formations. Indicates cased intervals. Logging in oil-based muds.	Fluid-filled or dry cased or uncased hole. Formations relatively free from shaly material. Diameter less than 6" for dry holes. Hole diameter similar throughout.
Density	Used as a porosity logging tool. Other uses include identification of minerals in evaporite deposits, detection of gas, determination of hydrocarbon density, evaluation of shaly sands and complex lithologies, and detecting grout.	Fluid-filled or dry uncased holes.
INDUCTION LOGGING	Determining true resisitivity, particularly for thin beds (down to about 2' thick) in wells drilled with comparatively fresh mud. Determining resistivity of formations in dry holes. Logging in oil based muds. Defining lithology and bed boundaries in hard formations. Detection of water bearing beds.	Fluid-filled or dry uncased hole. Fluid should not be too salty.

Table 12 (Continued)

METHOD	USES	RECOMMENDED CONDITIONS
Microlog	Determining permeable beds in hard or well consolidated formations. Detailing beds in moderately consolidated formations. Correlation in hard rock regions. Determining formation factor in sites in soft or moderately consolidated formations. Detailing very thin beds.	Fluid-filled uncased hole. Bit-size holes (caved portions of hole only logged if enlargements are not great).
Microlaterlog	Determining detailed resistivity of flushed formation at wall of hole when mudcake thickness is less than 3/8" in all formations. Determining formation factor and porosity. Correlation of very thin beds.	Fluid-filled uncased hole. Thin mudcake. Salty mud permitted.
Spontaneous potential	Helps delineate boundaries of formation and the nature of these formations. Determine values of formation-water resistivity. Qualitative indications of bed shaliness.	Fluid-filled uncased hole. Fresh mud.
RADIATION LOGGING: Gamma ray	Differentiating shale, clay, and marl from other formations. Correlation of formations Measurement of inherent radioactivity in formations. Checking formation depths and thickness with reference to casing collars before perforating casing. For shale differentiation when holes contain very salty mud. Radioactive tracer studies. Logging dry or cased holes. Locating cemented or cased intervals. Logging in oil-based muds. Locating radioactive ores. In combination with electric logs for locating coal or lignite beds.	Fluid-filled or dry cased or uncased hole. Should have appreciable contrast in radioactivity between adjacent formations.
SONIC LOGGING	Logging acoustic velocity for seismic interpretation. Correlation and identification of lithology. Reliable indication of porosity in moderate to hard formations, in soft formations of high porosity it is more responsive to the native rather than the quantity of fluids contained in pores.	Not affected materially by the type of fluid, hole size, or mud invasion.
TEMPERATURE LOGGING	Locating approximate position of cement behind casing. Determining thermal gradients. Locating depth of lost circulation. Locating active gas flow. Used in checking depth and thickness of aquifers. Locating fissures and solution openings in open holes and leaks or perforated sections in cased holes. Reciprocal-gradient temperature log may be more useful in correlation work.	Cased or uncased hole. Can be used in empty hole if logged at very slow speed, but fluid preferred. Fluid should be undisturbed (no circulation) for 6 to 12 hours minimum before logging; possibly several days may be required to reach thermal equilibrium.
	Locating point of entry of different quality water through leaks or perforations in casing or opening in rock hole. Determining quality of fluid in hole for improved interpretation of electric logs. [illegible]	Fluid required in cased or uncased holes. Temperature log required for quantitative information.

METHOD	USES	RECOMMENDED CONDITIONS
FLUID-VELOCITY LOGGING	Locating zones of water entry into hole. Determining relative quantities of water flow into or out of these zones. Determining direction of flow up or down in sections of hole. Locating leaks in casing. Determining approximate permeability of lithologic sections penetrated by hole or perforated section of casing.	Fluid-filled cased or uncased hole. Flange or packer units required in large diameter hole. Caliper log required for quantitative interpretation. Injection, pumping, flowing, or static surface conditions.
CASING-COLLAR LOCATOR	Locating position of casing collars and shoes for depth control during perforating. Determining accurate depth reference for use with other types of logs.	Cased hole
CEMENT BOND LOGGING	Used to assess the quality of the cement-to-using bond around a cemented casing.	Cased hole
CALIPER (SECTION GAGE) SURVEY	Determining hole or casing diameter. Indicates lithologic character of formations and coherency of rocks penetrated. Locating fractures, solution openings, and other activities. Correlation of formations. Selection of zone to set a packer. Used in quantitative interpretation of electric, temperature, and radiation logs. Used with fluid-velocity logs to determine quantities of flow. Determining diameters of underreamed sections for placement of gravel pack. Determining diameter of hole for use in computing volume of cement to seal annudar space. Evaluating the efficiency of explosive development of rock wells. Determining construction information on abandoned wells.	Fluid-filled or dry cased or uncased hole. Does not give information on beds behind casing in a cased hole.
DIPMETER SURVEY	Determining dip angle and dip direction (from magnetic north) of a bedding plane in relation to the well axis. A comprehensive study of computed data from a dipmeter survey makes possible the identification of faults, unconformities, cross bedding, sand bars, reefs, channels, deformation around salt domes, and other structural anomalies.	Fluid-filled uncased hole. Directional survey (see below) required for determination of true dip and strike (generally obtained simultaneously with dipmeter curves).
DIRECTIONAL (INCLINOMETER) SURVEY	Locating points on a hole to determine deviation from the vertical. Determining true depth. Determining possible mechanical difficulty for casing installation or pump operation. Used in determining true dip and strike from dipmeter survey.	Fluid-filled or dry uncased hole.
MAGNETIC LOGGING	Determining magnetic field intensity in borehole and magnetic susceptibility of rocks surrounding hole. Studying lithology and correlation, especially in igneous rocks.	Fluid-filled or dry uncased hole.

measured and the water surface elevation, relative to the datum, is determined. These data are used to prepare contour maps that depict the configuration of the piezometric surface and/or the water table.

Depth-to-water measurements can be made in a variety of ways (Garber and Koopman, 1968; USDI, 1977). Static water levels are conveniently and accurately measured with a chalked steel tape with a weight attached. The lower end (usually 5 to 10 ft) of the tape is coated with chalk. The chalked portion is lowered into the well until part of the chalked portion is wetted by the water standing in the well. The wetted portion changes shade, permitting the investigator to determine the distance between the reference point and the water level. The depth-to-water can be read to a precision of 0.01 ft. Accuracy of the depth to water will depend upon the degree to which the tape hangs plumb from the reference point, the temperature relative to tapes calibration temperature and other factors.

The necessity for withdrawing the tape from the well for each determination creates a serious disadvantage when several measurements must be made over small time intervals as in the case of aquifer testing. An electrical or acoustical sounder does not have this disadvantage. An electrical sounder consists of a spool of length-calibrated, insulated electrical cable, a water level sensor, an indicator meter, and a battery. Upon contact with the water surface, an electrical circuit is completed which causes the meter to deflect. The operator raises and lowers the probe slightly to find the exact point of contact with the water surface. The cable is usually calibrated in 5 ft intervals and interpolation between markers with a measuring tape is required. A precision of 0.01 ft can be achieved with practice. Accuracy is substantially affected by kinking of the cable and frequent calibration with a steel surveyor's tape is recommended.

The acoustical sounder consists of a steel tape with a resonator attached to the lower end. The resonator is usually a hollow cylinder about 2 inches long and 3/4 inch in diameter, capped on the upper end. The resonator makes a dripping or popping noise when contact is made and broken with the water surface in the well. The precision of this method is about 0.02 ft. The accuracy is affected by factors previously noted. This method will not be suitable when pump or other noise is sufficient to mask the sound of the resonator.

In cases where the piezometric surface elevation is above the top of the well casing, the well is equipped with a cap that is drilled and tapped in a way suitable for attachment of a pressure gage or mercury manometer. The readings from the pressure gage or manometer are converted to water pressure head and added to the elevation of the measuring point to determine the piezometric surface elevation.

None of the above described methods are suitable for continuous (or nearly continuous) measurements of water levels. Continuous water level records are useful for correlation of water level changes with precipitation and barometric pressure changes. Continuous water level measurements are usually made by attaching a float and a weight to opposite ends of a beaded cable. The cable is suspended over a pulley attached to a drum. As the float elevation changes in response to water level fluctuations, the drum is rotated. The rotation of the drum is recorded by an ink trace on coordinate paper wrapped about the drum. The ink marker is driven laterally along the drum with time by a spring or battery powered clock. A record of the depth-to-water over time is produced. Continuous water level recorders are produced commercially; the Stevens Type F recorder being one example. Independent measurements

of the water level should be recorded on the chart each time the chart is changed.

b. Hydraulic Coefficients of Aquifers

Essentially all quantitative studies of groundwater require the determination of the capacity of the water bearing materials to store and transmit water. In confined (artesian) aquifers the capacity to store water is characterized by the storage coefficient defined as the volume of water released from storage from a column of aquifer of unit cross-sectional area and length equal to the aquifer thickness when the piezometric head is reduced by one unit (McWhorter and Sunada, 1977). The storage coefficient is a dimensionless number and usually is in the range of 10^{-6} to 10^{-3}. The storage coefficient for coal and overburden aquifers in Colorado, Montana, and Wyoming is often about 10^{-5}.

In unconfined (water table) aquifers the capacity to store water is characterized by the apparent specific yield, defined as the ratio of the volume of water added or removed directly from the saturated aquifer to the resulting change in the volume of saturated aquifer (McWhorter and Sunada, 1977). The apparent specific yield is dimensionless and usually is in the range of 0.05 to 0.3.

Hydraulic conductivity (also known as permeability) is the coefficient in Darcy's law that relates the discharge per unit area in a particular direction to the rate of change of piezometric head with respect to distance measured in that direction. When the hydraulic conductivity is multiplied by the thickness of the aquifer, the resulting coefficient is called transmissivity.

A large number of field tests have been devised for the determination of the hydraulic coefficients. The basic idea behind all such tests is

to create a flow in the aquifer that can be described mathematically, to measure one or more aquifer responses to the created flow, and to determine the hydraulic coefficients by fitting or matching the measured response to the theoretical response.

Field tests vary tremendously in regard to expense, time, and data provided. One of the most important determinants of expense is number of observation wells required for the test. For example, tests conducted on an individual drill hole are less expensive than full scale aquifer tests that require at least one additional well for the observation of aquifer response. Nearly always, there is a trade off between the expense of the test and quantity and quality of information obtained.

Table 13 is a summary of several available test methods that can be used to determine the hydraulic coefficients of aquifers. A brief description of the actual procedures to be followed for each test are contained in the following paragraphs. Data analysis procedures are discussed in a subsequent section of the handbook.

Regardless of the type of test selected, the holes must be properly conditioned to insure a free transfer of water to and from the aquifer. This is usually accomplished by surging, pumping, bailing, wall scratchers or some combination of these procedures. The importance of these operations cannot be over emphasized.

(1) Pumping Test

A pumping test is conducted by measuring the water level drawdown in the pumped well and one or more observation wells in response to pumping at a constant and measured rate. All well construction data should be known in detail. Pumped water must be disposed of so that it does not recharge the aquifer during the test. The duration of the test can

Table 13. SUMMARY OF AQUIFER TEST METHODS

Test	Reference	Major Items Required	Parameters Obtained*	Comments
Pumping	McWhorter & Sunada, 1977; USDI, 1977; Stallman, 1971; Walton, 1962; Ferris & Knowles, 1963; Ferris et al., 1962.	Minimum of one observation well and preferably 4 or more; pump; power source; winch; tripod, mast or boom; discharge measuring device; stop watch; water level sounder.	T,K,S	Yields parameter values averaged over a relatively large aquifer volume; most commonly used when accuracy and reliability is of high priority; best results in aquifers with good continuity and permeability provided by intergranular flow channels; can provide evidence of leakage through aquitards, directional permeability, and the presence of hydrogeologic boundaries. -Relatively expensive, doesn't work well in very tight aquifers, requires a power source.
Drawdown/ specific capacity	Walton, 1970; USDI, 1977.	Same as above, but no observation wells are required.	T,K	Yields only rough estimates of T and/or K; storage coefficient or apparent specific yield must be estimated independently; conditions immediately adjacent to the well bore, well losses, etc. substantially effect results; in tight aquifers the effects of well-bore storage may be highly important. -Relatively inexpensive; most useful in reconnaissance investigations.

Table 13. (Cont'd)

Test	Reference	Major Items Required	Parameters Obtained*	Comments
Recovery	same as for pumping test.	same as for drawdown/ specific capacity.	T,K,S	Recovery should always be monitored following a drawdown/ specific capacity test; usually yields more reliable values for T and K than the drawdown/specific capacity test; has the additional advantage of providing an estimate of storage coefficient or apparent specific yield; because the rate of recovery is dependent upon the preceeding pumping rate the results are effected by well-bore storage. -Minimum expense in addition to that incurred during the pumping period and provides additional and more reliable information than the drawdown/specific capacity test.
Pressure pump-in	USDI,1977.	Inflatable or compression packers; pump; power source; pressure gages; stop watch; in-line discharge measuring device; storage capacity and source for water.	T,K	Usually conducted during exploration or reconnaissance investigations; permits determination of T and K in different intervals along the well bore; can be used above or below the water table or water level in the well; works best in consolidated aquifers or perforated well casing. -Relatively expensive because it is usually conducted during the drilling operations using the contractors rig and equipment.

Table 13. (Cont'd)

Test	Reference	Major Items Required	Parameters Obtained*	Comments
Slug/falling head	McWhorter & Sunada,1977; USDI,1977; Ferris & Knowles,1963; Kvorslev,1951; Papadopulos et al.,1967; Bouwer,1978.	Equipment required depends upon the manner in which the slug is added or removed. Pump may be used but is not required.	T,K	One of the simplest and least expensive of all tests; does not require a power source; yields values acceptably accurate for most purposes; analysis procedures available that account for aquifer storage only, well-bore storage only, or both. Applicable in both confined and unconfined aquifers.
Auger hole	Boast & Kirkham, 1971.	Small pump or bail; stop watch; float.	K	Applicable in cases of unconfined aquifers when the water table is within a few feet of ground surface; inexpensive, rapid, reliable.

*T = transmissivity
K = hydraulic conductivity
S = storage coefficient or specific yield.

range from a few hours to several days. Long test periods usually provide better results but are more expensive.

Observation well location is important, and the projected duration of the test, probable aquifer properties and whether or not the pumped well is fully penetrating should be considered in the selection of well spacing. In most coal and overburden aquifers in the Rocky Mountain region, transmissivities are small and the cone of drawdown does not expand rapidly. Estimates of the time rate of expansion of the drawdown cone can be made by procedures outlined by McWhorter and Sunada (1977). Rough estimates of pumping rate, transmissivity and storage coefficient are required. In very tight aquifers, at least one well should be within approximately 50 ft of the pumped well to insure measurable drawdowns within a test period of a few hours. Highly heterogeneous overburden caused by highly variable and discontinuous strata also dictate close spacing of the observation wells. The observation wells should be open for flow only in the stratagraphic interval being tested. When several observation wells are to be used, one-half of the total number should be located on a line passing through the pumped well and the remainder on a similar line at right angles to the first. This procedure may permit detection of directional permeability, for example.

The above described pumping test has been used widely for estimation of transmissivity and storage coefficient of aquifers supplying water to industry, agriculture, and municipalities. The pumping test becomes less suitable for aquifers that exhibit low transmissivities, highly variable and discontinuous stratigraphy, and fracture porosity and permeability. Unfortunately, many coal and overburden aquifers in the Rocky Mountain region exhibit all of these characteristics, and evenly, properly planned

tests have sometimes failed to provide data sufficient to justify the expense of such elaborate tests.

(2) Drawdown/Specific Capacity Test

This test is conducted by measuring the drawdown in the pumped well during the pumping period. The pump discharge must be maintained as nearly constant as possible. Ideally, the measured drawdowns can be analyzed to provide estimates of transmissivity and storage coefficient. Usually it is possible to estimate only transmissivity, however, and this should be regarded as only a rough estimate.

In very tight aquifers, a very small discharge can be supplied by the aquifer and difficulty with adjusting the pump discharge to a suitable low value is often experienced. Often, a substantial portion of the constant pump discharge is supplied by the water standing in the well, the remainder being contributed by inflow from the aquifer. Measurements of the water level in the well can be used to determine the contribution from wellbore storage and the pump discharge can be corrected to obtain the aquifer discharge. A good deal of inaccuracy is usually involved.

(3) Recovery Test

The recovery test provides estimates of the aquifer properties by measuring the recovery rate of water levels in the pumped well after pumping has ceased. It is especially useful when conditions do not permit the construction of observation wells. More precise data can be obtained during recovery than during the pumping period because water in the well is not disturbed by the pump. Total pumping time, average discharge rate from the aquifer, and the water level at various times since pumping ceased are measured. Estimates of both transmissivity and storage coefficient are obtained.

In the study of ground water at prospective surface mining sites, the recovery test has been found to be one of the best tests when the information obtained and costs are compared with other methods.

(4) Pressure Pump-In Test

There exist several variations of this test method. One variation is to terminate the drilled hole at the bottom of an interval to be tested. The drill tools are removed and a packer is set at a given distance above the bottom of the hole. Water is pumped into the test section between this packer and the bottom of the well and the flow rate and injection pressures are recorded over a period of time. These data, together with detailed data on depths, test interval, pipe sizes, etc. permit the estimation of the average hydraulic conductivity and transmissivity over the test interval. The packer is then removed, the hole deepened, and the test repeated as desired. Another variation is to drill the hole to total depth and use straddle packers to isolate intervals of interest for testing. The test is started at the bottom of the hole.

The pressure pump-in test has been used extensively for foundation investigations associated with reservoirs, conveyance facilities and other construction projects. The method has also proven useful in hydrologic investigations, however.

(5) Slug/Falling Head Test

Briefly, the water level in the well is changed instantaneously by the rapid withdrawal or displacement of a volume of water. The water level recovery in the well is measured with respect to time. Slug tests are an economic means of determining local trnasmissivities near the well. In some types of groundwater investigations (tight aquifers), a large number of "point" transmissivities are of more value than a single

value of transmissivity obtained from a long-term pumping test of equal cost (Papadopulos et al., 1973). Slug tests can also be an indicator of the effectiveness of well development. In a properly developed well, the slug test transmissivity should be greater than the long term pump test transmissivity (Papadolulos et al., 1973).

The following considerations should be made prior to conducting a slug test (adapted from Cooper et al., 1967):

1. Wells should be fully developed, that is, surged and pumped thoroughly to establish a good transfer of water between the well and aquifer.

2. Wells should completely penetrate the aquifer.

3. Well construction data should be known in detail.

4. Provisions must be made to quickly remove a known volume of water (by bailer) or quickly displace the water with a "slug". A convenient displacement slug is a length of weighted water pipe sealed at both ends (a 3-inch diameter, 10-foot long pipe displaces a volume of about 0.49 ft^3).

The slug test proceeds as follows:

1. Quickly immerse the slug or remove a known volume of water from the well.

2. Record the time when the slug is immersed.

3. Record the water levels and elapsed time.

4. Make water level readings at 1 or 2 minute intervals for the first several minutes of the test and gradually increase intervals to 10-20 minutes after one hour. Half-hour intervals are usually sufficient after two or three hours.

The falling head test is essentially the same ad described above. One variation is to set a packer above the zone to be tested. The head is increased by adding a known volume of water to the stinger pipe extending through the packer. The dissipation of the head is monitored by measuring the water level in the pipe.

(6) Auger Hole Test

This test is useful only when the water table is within a few feet of the ground surface. A hole is augered to a depth that insures the bottom of the hole is a few feet below the water table. A perforated casing is required in materials that tend to cave and bridge the hole. After the hole is cleaned and the water level stabilized, the hole is pumped or bailed dry as quickly as possible. The water level recovery is measured as a function of time, usually by means of a float. The hole depth, hole diameter, depth to the water table and certain geologic information permit the estimation of hydraulic conductivity. This test is most useful in shallow water table aquifers associated with streams or in perched aquifers.

The above descriptions are provided to give the reader, unfamiliar with such tests, sufficient insight to decide what test or tests may be suitable for a particular problem given a set of financial, time, and equipment constraints. The references provided in Table 13 should be consulted for additional details.

D. Laboratory and Greenhouse Studies

1. Soils and Geologic Overburden Characterization

a. Stratigraphic Framework

(1) Core Descriptions - Lithologic Logs

Continuous cores or rock chips and cuttings from bore holes that

penetrate the overburden should be described and lithologic logs prepared by qualified geologists or soil scientists. Drillers logs of each borehole may be available, however, reliance should not be placed on these as satisfactory core descriptions. Information contained in these lithologic logs should include at a minimum: project number, core hole location, core hole number, depth from the surface, rock name, color, texture, accessory constituents (gypsum, pyrite, iron oxide, calcite, etc.), percentage of lost core or intervals of lost or broken core, inducation, and general descriptions of each rock unit. A simple lithologic log used for description of cores for the SEAM study site in the Powder River Basin is included as Fig. 8. Most mining companies have standard formats for core logs. These formats will vary from company to company. Recently, several computer oriented formats have come into use (Blachet and Goodwin, 1972); Ekstrom, Wirstam, and Larsson, 1975; Melton and Frem, 1978; and Lehmann, 1978). With these methods much of the logged data can be processed by computers and graphically displayed in a standard format.

A color photographic or color slide record of all cores should be made as a permanant record of the cores as soon as possible after core recovery (Fig. 9). Samples from continuous cores or cutting should be taken for detailed laboratory studies of mineralogy, texture, and geochemistry of each major rock unit encountered as discussed in the section prior to this. Core samples may also be required for geotechnical data such as the strength of intact rock, discontinuities, hardness and abrasion, blastability, rippability, and general visual assessment of likely engineering behavior of the materials (Dames and Moore, Vol. II, 1976). Most of this type of information can only be obtained from cores, whereas

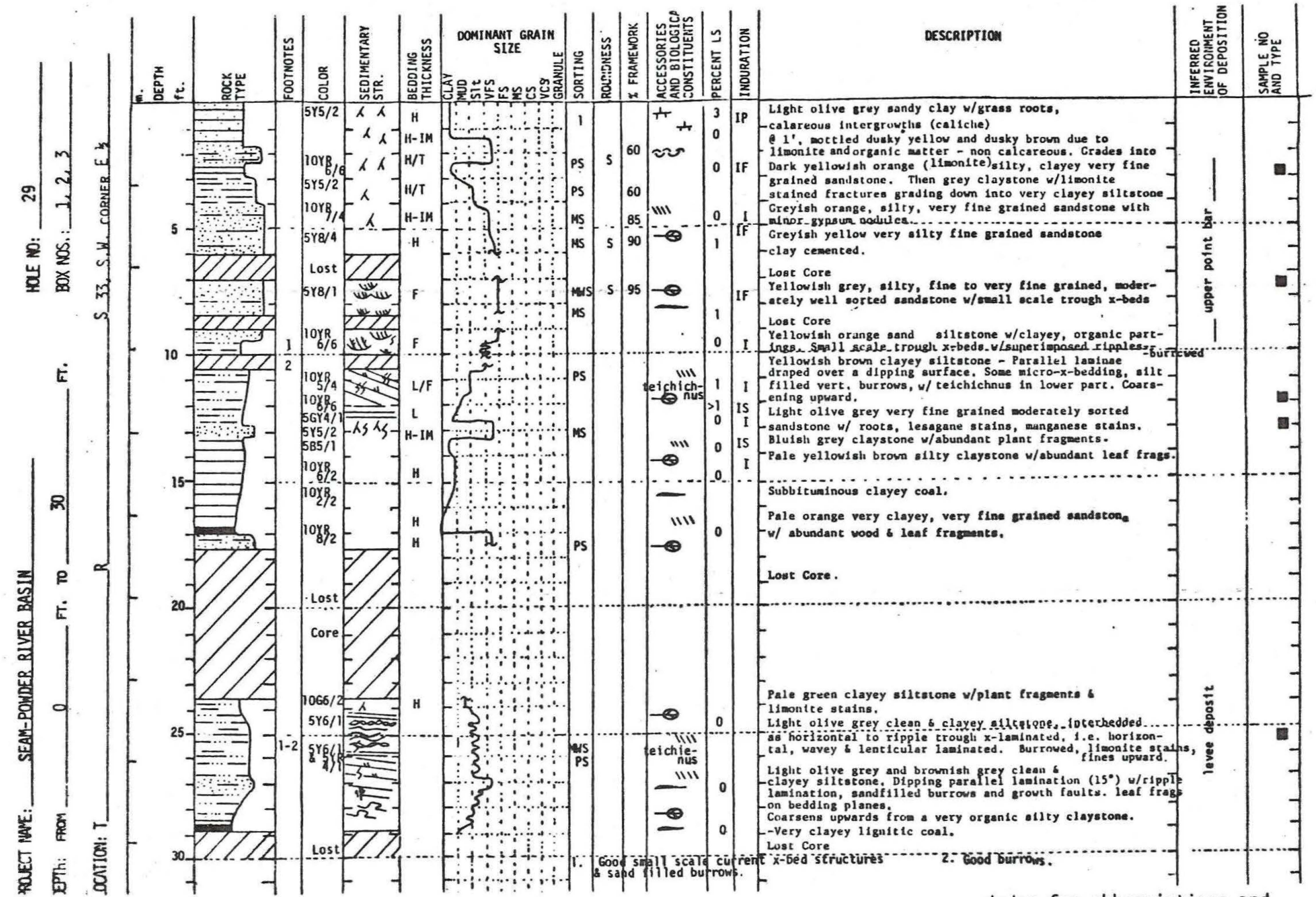


Figure 8. Example of format for lithologic logs.

codes for abbreviations and symbols given in Appendix II

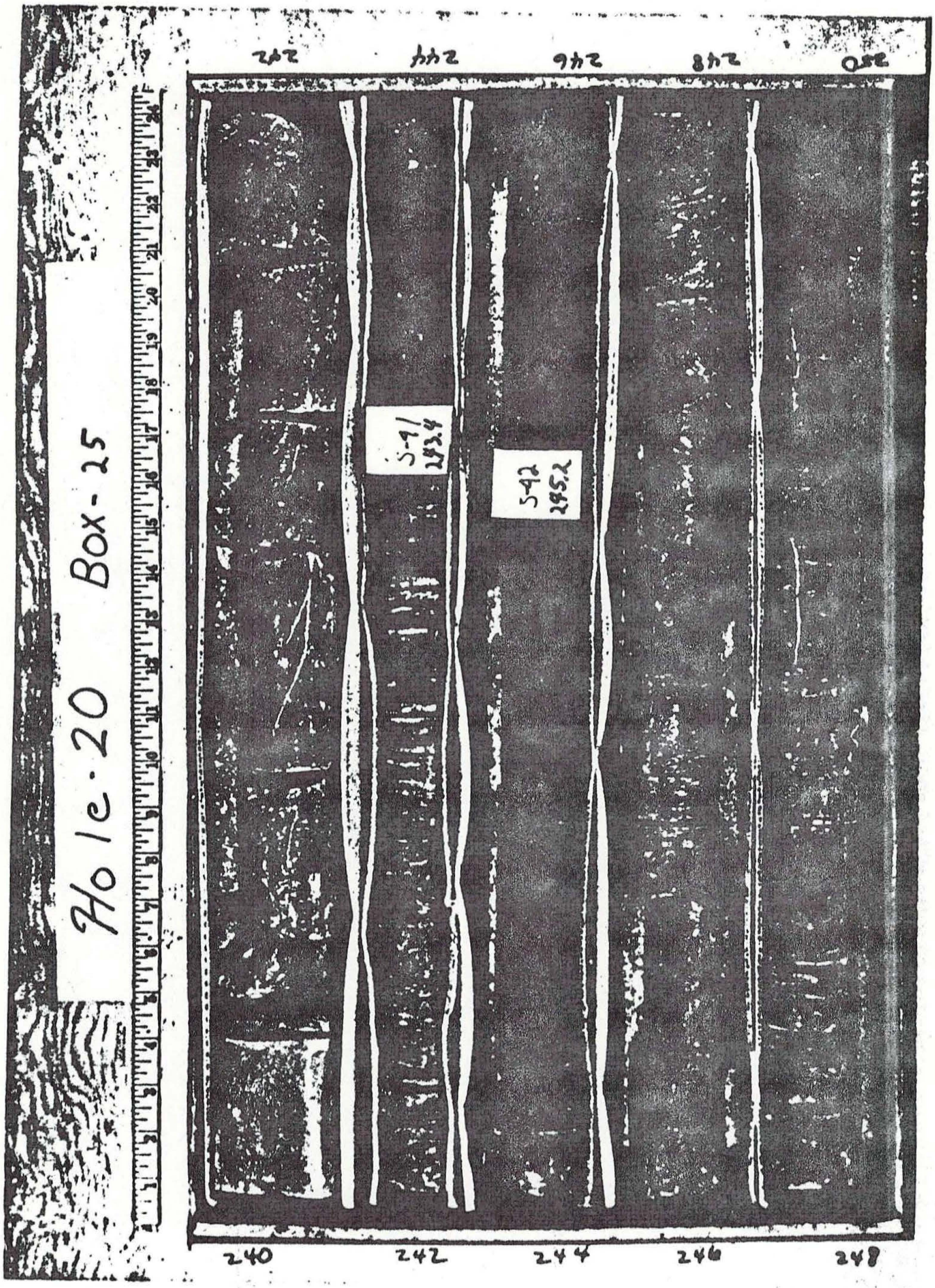


Figure 9. Photograph of core from SEAM study site, Powder River Basin, Wyoming.

it is possible to obtain some stratigraphic data from cuttings alone.

(2) Stratigraphic Studies

Definition and importance - Stratigraphy is that branch of geology that deals with the study and interpretation of stratified and sedimentary rocks and with the identification, description, sequence (both vertical and horizontal), mapping, and correlation of stratigraphic rock units (Weller, 1960). Stratigraphic sequences range from simple, where rock units underlying an area are uniform in thickness and character, to very complex, because of lateral changes in rock type, thickness, presence of unconformities, and/or intense structural implications. An understanding of the stratigraphic framework of the overburden is of fundamental importance to the design of open pit mines, the handling of undesireable and/or toxic materials, the design of reclamation plans, and the understanding of groundwater flow patterns.

Methods - Determining the stratigraphic framework of the overburden can be accomplished by evaluation and correlation of some combination of the follow down the hole records of overburden material: geophysical logs, drill hole cuttings, and continuous cores. The stratigraphic framework cannot be determined on the basis of geophysical logs alone in areas where no drill hole cuttings or cores are available. Examination of core or cutting data in the field or laboratory provides direct information concerning the physical characteristics of the overburden and provides the basis for interpretation of geophysical logs. Once the relation between geophysical log patterns and lithologies has been substantiated, the logs become more dependable tools for interpreting overburden lithologies.

When all the information from cores, cuttings, and/or geophysical logs is assembled, the thickness, elevation, distribution, geometry, and

variability of the overburden and various rock units within the overburden can be portrayed by some combination of the following visual techniques: isopach maps, cross-sections, and fence diagrams, and structural contour maps.

An isopach map is a map in which the shape (distribution, thickness) of a body (a rock unit) is indicated by lines drawn through points of equal thickness. The lines are analogous to contour lines but represent thickness rather than elevations or altitude. A typical isopach map is shown in Fig. 10. Isopach maps are useful not only in showing the total thickness of overburden and interburden units within the overburden, but can also be used to show the lateral variation in content of some toxic element within the overburden if thickness measurements are replaced with percentage or parts per thousand, million, etc. values.

A cross-section is a profile portraying an interpretation of a vertical section of the earth (in this case the overburden) (Fig. 11). A fence diagram is a combination of three or more geologic cross-sections showing the relationships of wells to subsurface formations (rock units). When several sections are used together they form a fencelike enclosure, hence the name (Fig. 11). Cross-sections and fence diagrams are useful for displaying the two and three dimensional attitudes, thicknesses, and distributions of various rock units within the overburden and the overall stratigraphic framework of the area of a proposed surface mine.

A structure contour map is a map displaying contour lines drawn through points of equal elevation on a strata, key bed, or some other horizon in the overburden in order to depict the attitude of the rocks (Fig. 12). Such maps will certainly be required of the top and possibly the bottom of all coal seams to be mined in surface coal mining operations.

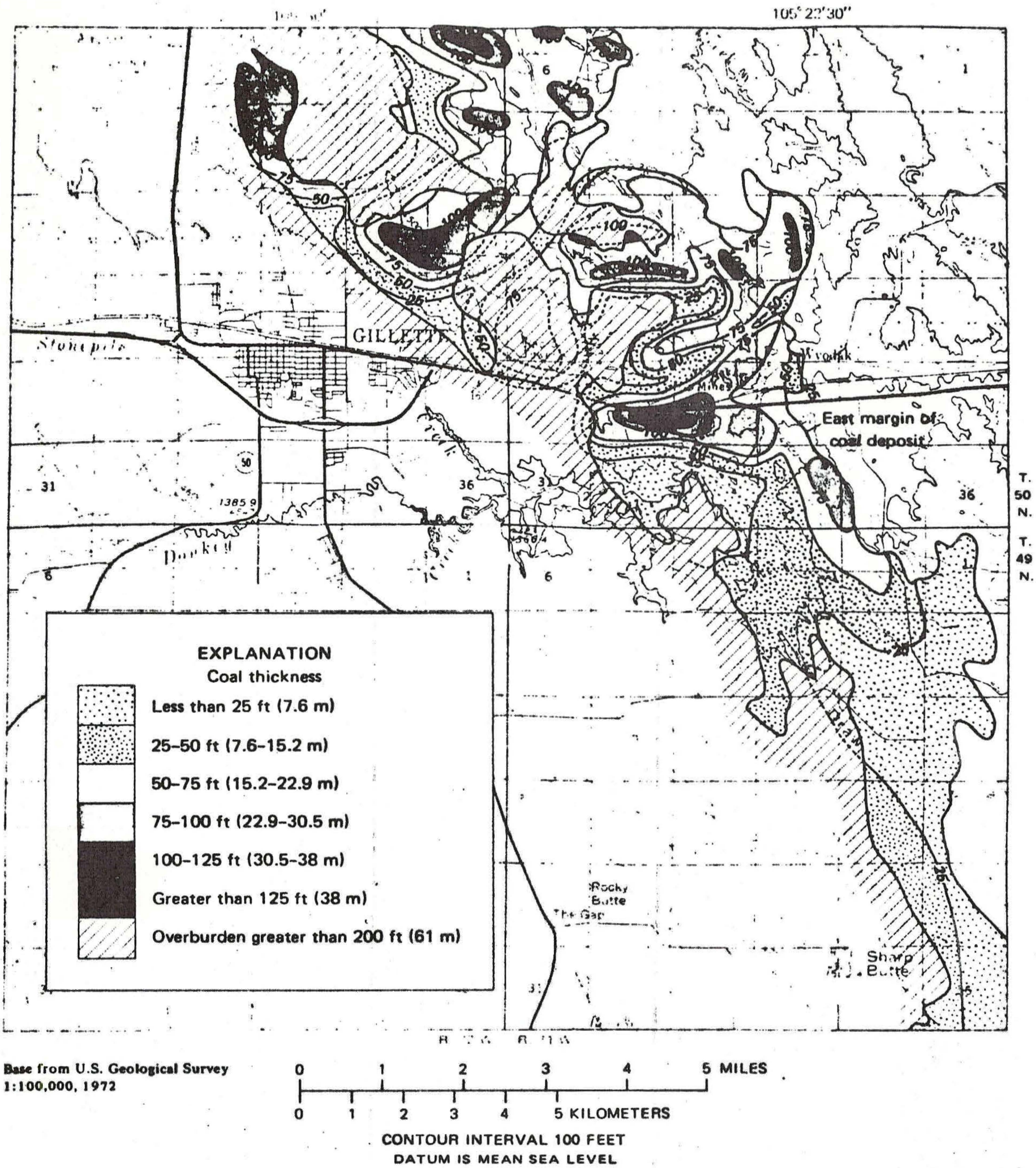


Figure 10. Isopach map of strippable coal zone, Wyodak-Anderson coal deposit, showing thickness of coal with contour lines and patterns. Contour interval equals 25 feet (7.6 meters) (after Keefer and Hadley, 1976, fig. 7, p. 10).

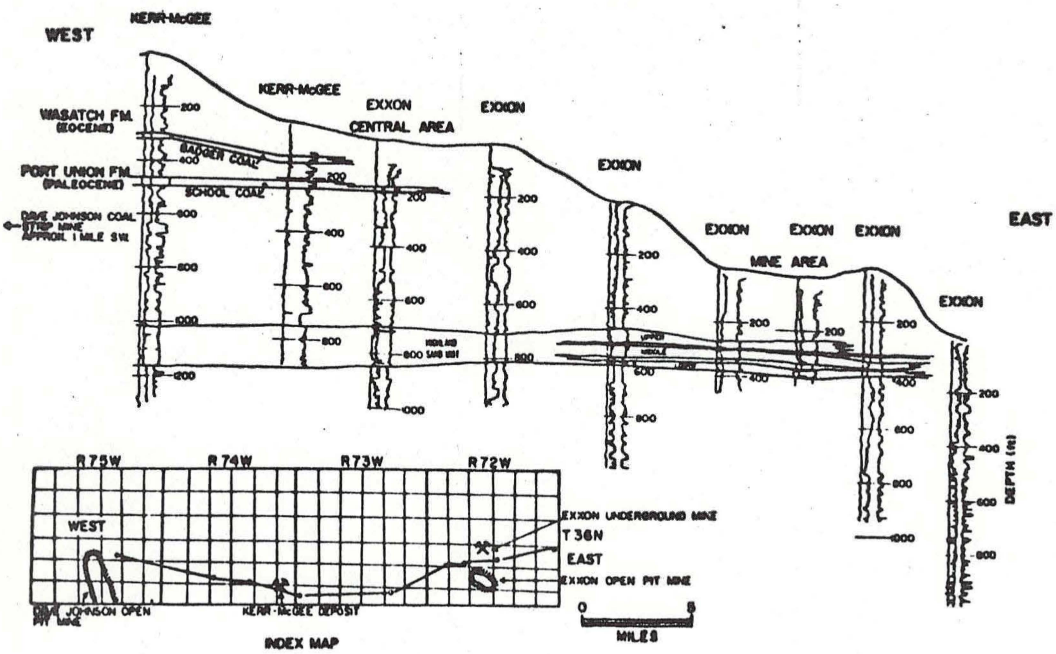


Figure 11A. Stratigraphic cross-section between Dave Johnson Coal Field and Highland area, southern Powder River Basin, Wyoming (after Dahl and Hagmaier, 1974, p. 207, figure 6).

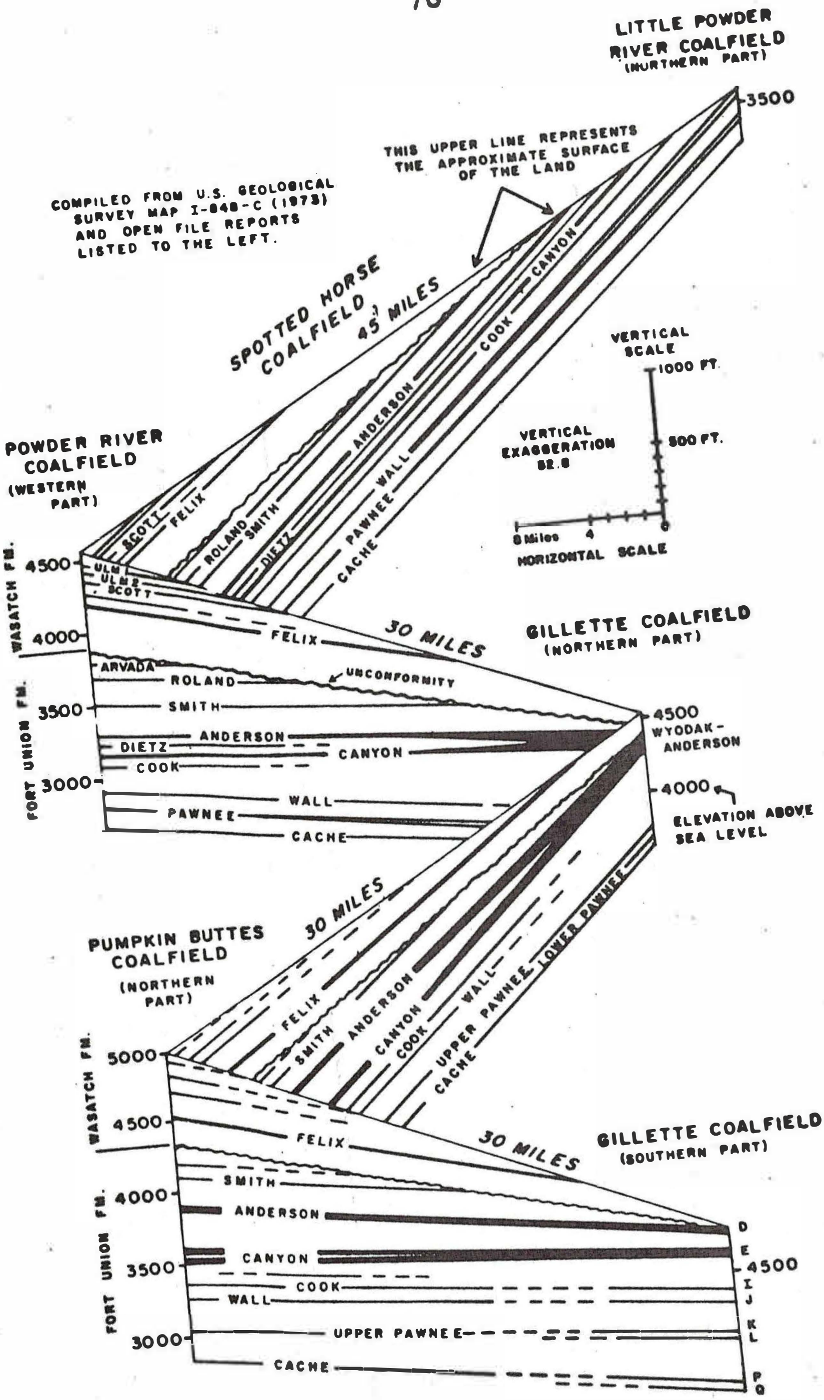


Diagram Showing Correlation and Thickness of Major Coal Seams

Figure 11B. Fence diagram showing correlation and thickness of major coal seams, Campbell County, Wyoming (after Breckenridge, Glass, Root, and Wendell, 1974).

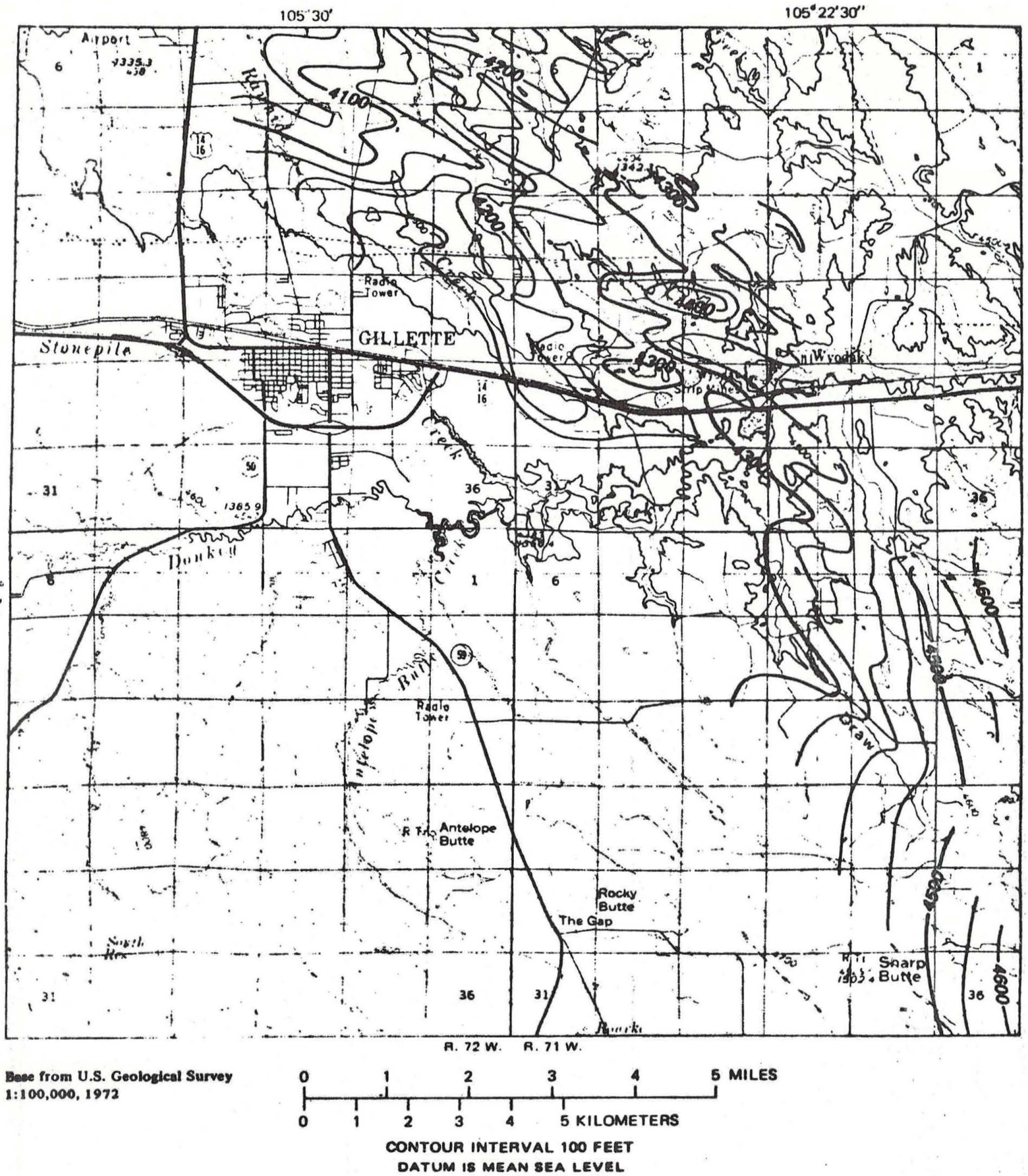


Figure 12. Structure Contour Map drawn on base of Wyodak-Anderson coal, Gillette and vicinity. Contour interval is 50 feet (15 m.); datum is mean sea level; hachures point toward areas of lower elevation. Strippable coal zone, Wyodak-Anderson coal deposity is shown by shading (after Keefer and Hadley, 1976, fig. 6, p. 9).

The number and type of stratigraphic maps, cross-sections and fence diagrams will of course be a function of the complexity of the local stratigraphic framework. However, it seems likely that at least some of these mathods will be employed to convey a visual picture of the stratigraphy of the geologic overburden material and the presence and distribution of units that have undesirable characteristics of toxic materials.

b. Analysis of Soils and Overburden Samples

(1) General

The most prevalent problems reported to occur in relation to strip-mine reclamation in western arid-land areas are: 1) shallow topsoil depths and low fertility status of topsoil, subsoils, and overburden; 2) excessive soil salinity and exchangeable sodium in soils and overburden; and 3) high clay content of subsoils and overburden. Therefore, the analyses listed in Table 14, center around characterizing soil and overburden for these problems. In most cases, the same analytical procedures may be used for both soil and overburden samples. However, soil samples should not be taken from cores or cuttings used for overburden characterization.

Most of the analyses listed are well-tested and standardized. Thus, the procedures are listed as "acceptable". One procedure source is listed in most cases, a source that is readily available or accessible. It is not intended to restrict the analytical methods or instrumentation used exactly to those used in the procedure cited. Any analytical instrument or method is acceptable that gives comparable or more accurate results or will correlate well with the procedures cited.

A screening procedure is given for some determinations such as potentially toxic elements and pyrite along with a more quantitative procedure where such acceptable procedures are available.

Table 14. ANALYSES FOR CHARACTERIZING SOIL AND OVERBURDEN SAMPLES.

SOIL OR OVERBURDEN	REPORTED AS	IMPORTANCE OF AND/OR USE	ACCEPTABLE PROCEDURE[1]
<u>Salinity-Exchangeable Sodium-Related Analyses and Calculations</u>:			
Saturated paste	Water saturation - % (SP)	Measure of maximum moisture retention of pulverized (<2 mm) soil or overburden; ½ SP gives an estimate of field capacity of unconsolidated material; ¼ SP gives an estimate of wilting point of unconsolidated material.	USDA Agr. Handbook 525, No. 2, p. 4-6
Reaction (acidity or alkalinity)	pH of saturated paste (pH_s); pH of dilute soil: water suspension, usually 1:5 (pH_d); pH is the negative log of hydrogen in activity	Soil pH aids diagnosis of many different soil problems, such as an indication of free lime or excessive exchangeable sodium; pH is not very reliable when used as the only diagnostic criteria.	USDA Agr. Handbook 525, No. 4, p. 6
Electrical Conductivity Saturated Paste Extract	Millimhos/cm 2 25^{o}C ($ECx10^3$)	Rapid measure of water soluble salt content	USDA Agr. Handbook 525, No. 1, p. 22
Water Soluble Cations (Ca, Mg, Na, K)	Milliequivalents/liter; PPM; Milliequivalents/100 grams	Indication of cation distribution in soil solution and on cation exchange complex; assessment of salinity and fertility relationships	USDA Agr. Handbook 525, No. 2, 3, 4; p. 24-27
Sodium Adsorption Ratio (SAR)	$\frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$ (calculated in me/l)	Estimation of percent exchangeable sodium (ESP)	USDA Agr. Handbook 60, No. 20b, p. 102

[1]Reference citations given in literature citation section.

Table 14. continued

Potassium Adsorption Ratio (PAR)	$\frac{K}{\sqrt{\frac{Ca + Mg}{2}}}$	Estimation of Percent Exchangeable Potassium (EPP)	USDA Agr. Handbook 60, No. 20b, p. 102
Water Soluble Anions (CO_3, HCO_3, SO_4, Cl, NO_3, B)	Milliequivalents/liter, PPM; Milliequivalents/100 grams	Indication of anion distribution in soil solution; assessment of salinity-fertility relations	USDA Agr. Handbook 525, No. 5, 6, 7, 11, 12; p. 16-18, 20-22, 27-30
Ammonium Acetate Extractable Cations (Na, K)	Milliequivalents/100 grams	Determination of exchangeable sodium and potassium	USDA Agr. Handbook 525, No. 5, p. 7-8
Cation Exchange Capacity (CEC)	Milliequivalents/100 grams	Measure of total cation retention	USDA Agr. Handbook 525, No. 5B, p. 8-9
Exchangeable Sodium Percentage (ESP)	Percent	Measure of percent sodium on cation exchange capacity (not reliable for material containing sodium-zeolite)	USDA Agr. Handbook 525, No. 6, p. 9
Exchangeable Potassium Percentage (EPP)	Percent	Measure of percent potassium on cation exchange capacity	USDA Agr. Handbook 60, No. 20, p. 101
Gypsum	Milliequivalents/100 grams; Percent	Measure of solid phase gypsum content	USDA Agr. Handbook 525, No. 7, p. 10-11
Fertility-Related Analyses:			
Calcium Carbonate Equivalent	Percent; Milliequivalents/100 grams	Measure of alkaline-earth carbonates	USDA Agr. Handbook 525, No. 3, p. 6
Organic Carbon	Percent (readily oxidized carbonaceous residue of plant material)	Assessment of N and S fertility; stability of soil aggregates	USDA Agr. Handbook 525, No. 8, p. 12-13
Total Nitrogen	Percent, PPM	Assessment of N-cycling potential in terms of C/N	USDA Agr. Handbook 525, No. 10, p. 14-16
Acid Permanganate Oxidizable Soil Nitrogen	PPM	Assessment of potentially mineralizable soil nitrogen	Stanford and Smith, 1978

Table 14. continued

Ammonium, Nitrate, and Nitrite	PPM, Milliequivalent /100 grams	Indication of plant available nitrogen	USDA Agr. Handbook 525, No. 10B, p. 18-20
Available Phosphorus	PPM	Plant availability index	USDA Agr. Handbook 525, No. 9, p. 13-14; Watanabe and Olsen (1965)
Available Potassium	PPM	Plant availability index	ASA Monograph No. 9, Part 2. Pratt (1965), p. 1027-1030
DTPA Extractable Zinc, Iron, Manganese, and Copper	PPM	Plant availability index	Lindsay and Norvell (1978)
Toxicity-Related Analyses:			
Active Sulfides (Qualitative)	Present or Absent	Acidification potential	Neckers and Walker (1952)
Total Sulfur	PPM, Percent	Assessing acid-base potential	ASA Monograph No. 9, Part 2. Bardsley and Lancaster, 1965. p. 1103-8; Smith, et al, (1974, 1976)
Acid-Base Account	Tons per 1000 tons	Assessment of neutralization of potential acidity by lime	Smith, et al (1976), p. 293[2]
Elemental Analysis	PPM, Percent	Screening for potential heavy metal or other elemental toxicity	X-Ray Spectroscopy ASA Monograph No. 9 (Vanden Heuvel 1965,p771-819)
Hot water soluble Se	PPM	Assessment of plant toxicity	ASA Monograph No. 9, Fine (1965), p. 1122
Amonium oxalate extractable Mo	PPM	Assessment of plant toxicity	ASA Monograph No. 9, Reisenauer (1965) p. 1054
Hot water soluble Boron	PPM	Assessment of B-toxicity	USDA Agr. Handbook 525, No. 12, p. 20-22

[2] Water soluble sulfate and gypsum should be deducted from total sulfur

Table 14. continued

DTPA Extractable Zinc, Iron, Manganese, Copper, Cadmium (and probably other heavy metals)	PPM	Assessment of ion toxicities to plants	Lindsay and Norvell (1978); Korcak and Fanning (1978)
Physical Analyses:			
Particle size analyses	Percent sand, silt, clay (also very fine sand)	Assessment of erosiveness, permeability, water holding capacity, capillary potential inherent fertility	ASA Monograph No. 9, Day (1965), p. 545-566
Texture	sand, loamy sand, sandy loam, loam, silt loam, sandy clay loam, silty clay loam, clay loam, clay	Assessment of generalized moisture, fertility, and and salinity relations	USDA Texture Classification
Shrink-Swell	Low, Medium, High	Assessment of permeability hazard	ASA Monograph No. 9, Holtz (1965), p. 461-63
Slaking Test	Percent particles passing screen	Assessment of induration	Modification of Smith, et al, (1976)
Mineralogical Analyses:			
Pyrite Identification	Euhedral phenocrests, Framboidal; percent; present or absent; size	Acidification potential	Petrographic Analysis; X-Ray Diffraction, Electron Microscopy (Arora et al.,1978)
Clay Mineralogy	Clay mineral type; percent	Evaluate moisture and fertility relationships	ASA Monograph No. 9, Chs. 44, 45,49; p.568-601,611-696
Sand Mineralogy	Mineral, matrix, and cement percentages	Evaluate weatherability, strata, and fertility relationships	ASA Monograph No. 9, Cody (1965), p.604-630

(2) <u>Sample Selection Guidelines for Chemical, Mineralogical, Textural and Physical Analysis</u>

Criteria and guidelines for selecting and handling soil samples for laboratory characterization are given in Table 4. Approaches for sampling geologic overburden materials are discussed in the drilling section. The data requirements and sample selection criteria for geologic overburden might be greatly simplified if soils were characterized as to suitability and adequacy prior to overburden characterization. If it were know that sufficient soil materials were available for reclamation, then fertility analyses of geologic overburden and possibly other analyses such as textural analyses could be eliminated. The number of time-consuming analyses performed could be reduced considerably by a general screening program approach to the identification of pyrite and some potentially toxic elements. Pyrite can be expected to form in the presence of organic carbon and inorganic sulfur compounds in a reducing environment. Pyrite may be visible in euhedral crystals in overburden samples or in thin sections and is usually found in overburden with color chromas less than 3(Smith et al., 1976). A rapid qualitative chemical screening procedure can be used to determine the presence or absence of pyrite in the overburden strata. A more quantitative procedure can then be used on samples containing pyrite. A large number of potentially toxic elements can be determined simultaneously on one sample by total elemental analyses with emission spectroscopy. This procedure can serve as a screening procedure. Elements with high or marginal total concentrations can then be subjected to more specific quantitative analyses.

In general, all samples should be representative of the intervals to be sampled (equal amounts of the interval thoroughly mixed) so that

the quantitative significance of the analyses can be assessed. Also, it is recommended that enough extra sample be retained so that analyses can be repeated if necessary or for further analysis in case questions arise in the future.

2. Groundwater and Surface Water Chemistry

The use of proper sampling procedures for ground and surface water is imperative in order to ensure accurate water quality information. The field investigator must be sure that his sample is representative of the water body under investigation for decisions based upon water quality data are vitally dependent upon sample validity. It has been suggested that improper sampling location may yield the greatest source of error in the entire water quality data acquisition process (Hem, 1970). The following is a brief summary of proper sampling procedures; for additional information see Hem, 1970 and Rainwater and Thatcher, 1960.

a. Surface Water Sampling

The following criteria should be considered when establishing a surface water sampling network (adapted from Rainwater and Thatcher, 1960):

1. The water is completely mixed and of uniform composition.

2. Each sampling location fits into a comprehensive network for evaluating chemical composition throughout the study area.

3. The data gained from the sampling network can be correlated with information derived from other smapoing programs in the area.

4. The sampling location is such that estimates can be made of the amount of total dissolved material discharges from the area.

5. Location of the sampling point is at a transition from the surface outcrop of one geologic formation to another.

6. Location can be used to monitor both pre- and post-development water quality.

7. Locations provide information about the water quality upstream and downstream from the development area.

b. Groundwater Sampling

Water samples taken from idle, non-pumping wells are usually not representative of the groundwater chemistry. Well water above the screened interval is isolated from the aquifer and tends to be stratified and stagnant. Furthermore, this water may contain foreign material from the surface and include chemical compounds derived from the well casing and drilling fluids.

To avoid the collection of nonrepresentative, stagnant water samples, each well should be thoroughly flushed out prior ot sampling. For high capacity wells, three to five times the volume of water contained in the casing should be evacuated to obtain a representative sample. Low capacity wells should be pumped completely dry and allowed to recover; if recovery is rapid, the well should be completely evacuated two or three times prior to smapling. To ensure complete removal of the stagnant water, the pump screens or discharge line inlet whould be placed as near to the well screen as possible.

The following equipment is suitable for the collection of groundwater samples: 1) bailers, 2) surface pumps (peristaltic, centrifugal, vaccum), 3) submersible pumps, and 4) air lift equipment.

Care must be taken when using any of these devices for sampling purposes; improper handling and poor sanitation will compromise the worth of the water sample, possible leading to incorrect management decisions. Specifically, bailers should be used only when it is possible to completely

dry out the well by bailing, otherwise the sample is unreliable. Pumps and air lift equipment are probably the best means of collecting ground water samples. Unfortunately, all these devices tend to aerate the water sample which may affect the concentration of heavy metal ions and other constituents. Rapid sample preservation will minimize the aeration effects.

The following data should be collected at each surface and ground water sampling station.

Data	Surface water	Groundwater
Name of water body	X	X
Site location	X	X
Point of collection (pump discharge, etc.)	X	X
Method of collection	X	X
Time and date	X	X
Gage height or discharge	X	X
Temperature	X	X
Collector's name	X	X
Well number		X
Well depth		X
Well diameter		X
Screened interval		X
Static water level		X
Field conditions	X	X

c. Sampling Frequency

Water quality sampling frequency should be such that no important or significant changes in water quality go unnoticed between sampling times (Rainwater and Thatcher, 1960). In general, sampling frequency should be proportional to the variability of the water chemistry; stations with high water quality variability should be sampled more frequently than stations with consistant water quality. Obviously, the hydrologist must seek a compromise between the accuracy and detail desired in the water quality record and available funding. In most cases, quarterly or bi-annual sampling intervals are sufficient for confined groundwater quality studies. Unconfined groundwater may require more frequent sampling.

Higher sampling frequencies are usually required for most surface water stations due to the greater water quality fluctuations brought about by the variability in discharge and meteorological effects.

In some cases it is possible to reduce laboratory analysis costs by measuring a few "indicator constituents" at frequent intervals while performing more expensive complete analyese only when the indicators suggest significant water quality changes. Possible indicator constituents include temperature, electrical conductivity, pH, and alkalinity; these measurements should be done in the field.

d. Sample Preservation and Constituent Analysis

Sample preservation should never be regarded as absolute, as it is impossible to achieve complete stability for every constituent to be analyzed. Preservation techniques serve only to retard the chemical and biological changes that occur in the sample container. For this reason, it is essential that water samples be preserved as soon as they are collected and analyzed as soon as possible.

Laboratory-grade glass or plastic containers are suitable for the storage of most natural waters. Care should be taken that each sample bottle is absolutely clean. To ensure cleanliness each container should be treated as follows: wash each bottle thoroughly with detergent, rinse with tap water followed by a nitric acid rinse, rinse again with tap water and finally rinse with deionized water. Following this procedure each bottle should be sealed until needed. In the field each bottle should be rinsed thoroughly with the sample, then filled completely leaving as little entrapped air as possible.

The two most commonly used field preservation procedures are refrigeration and filter/acidification. For the refrigeration method the

sample is simply collected in the sample bottle then immediately cooled to below 4°C using ice or other means. The advantages with this method are that little sampling equipment or chemicals are needed and the procedure is simple. This method may not be practical, however, when sampling warm water or during hot days because large quantities of ice are required to ensure adequate cooling and preservation. If a constant temperature below 4°C cannot be maintained, then the filter/acidification procedure must be used. Filter/acidification requires the following equipment: prefilter papers, 0.45 micron filters, filter chamber (USGS or Skogstadt type), nitric acid, zero-impurities grade nitrogen gas (required only when minor elements or heavy metals are to be analyzed).

A portion of the water sample is placed in the pressurized filter chamber and forced through the filters at pressures below 15 psi. The filtered fraction is then stored in two separate portions; a one liter portion that has been filtered and then acidified with nitric acid to a pH of 2.0 and a 250 ml portion that has been filtered only. Also, 250 ml of raw water should be sampled in addition to the filtered portion. Each sample bottle should be labeled according to its field treatment; the nitric acid should be added directly to the one liter portion in the sample bottle. All water samples should be kept as cool as possible and out of direct sunlight regardless of the preservation method.

Due to preservation difficulties, some water quality parameters must be analyzed in the field in order to obtain accurate data. Analyses that must be done in the field include: temperature, electrical conductivity, pH, alkalinity, dissolved oxygen, carbonate, bicarbonate.

The following parameters should be analyzed in connection with pre-mining, mining, and post-mining water quality monitoring programs (from

Wyoming Department of Environmental Quality, Division of Land Quality Guidelines #4):

pH	arsenic	mercury
temperature	cadmium	nickel
total dissolved solids	calcium	nitrate (or N)
electrical conductivity	chromium	phosphorous
alkalinity	copper	potassium
hardness	flouride	selenium
carbonate	iron	sodium
bicarbonate	lead	sulfate
aluminum	magnesium	zinc
ammonia	manganese	

For uranium mines add: redox potential, molybdenum, vanadium, uranium, radium.

For surface water add: dissolved oxygen, total suspended solids.

The significance of each of the above constituents is discussed in USEPA (1976).

3. Greenhouse Studies and Plant Tissue Analysis

Perhaps one of the greatest problems facing both laboratories providing data and planners and land managers receiving these data is "interpreting" the meaning of many of the soil chemical and biological assay data that is being required for assessing the suitability of soil and/or geologic overburden as plant growth media. Public pressure has forced them into performing tests before they were ready with data needed to interpret these tests.

Thus, a serious gap exists for which calibration data is needed. This information can be supplied in several ways. Mainly through laboratory and/or greenhouse studies which give only partial answers; or mainly through field studies which require long periods of time and are subject to loss because of weather, diseases, etc., and the results of which are not always easily transferred from one site to another; or by a combined greenhouse, laboratory and field experimental program. The

latter approach is perhaps the most economical and efficient in terms of time and reliability.

The purpose of this section is not to infer that greenhouse and associated soil and plant diagnostic studies should always and everywhere be considered. Rather, the information is provided to encourage mining companies and/or agencies to develop research programs that are needed to fill critical data gaps.

The usefulness of greenhouse and plant tissue analyses studies has long been demonstrated in soil test-plant nutrient correlation studies on agronomic crops. And it seems fair to say that this approach is compatible as a basis for studying these same relationships associated with mined-land reclamation. Differences between them are probably more by degree than actual.

When one considers the multitude of conditions that exist in terms of soils, crops or vegetation types, climatic conditions and management alternatives associated with areas in which surface mining is taking place, it becomes apparent that field trials cannot, in a practical sense, be carried out in sufficient time to provide the calibration data needed. Greenhouse and associated soil and plant diagnostic techniques should be considered as a viable screening mechanism for identifying the nature and extent of potential soil-plant nutrient deficiencies and/or toxicities that might be associated with the soil-plant systems being managed. Data furnished from these types of studies can serve as a reliable basis for determining the variables that should be included in field experiments to better examine the system.

Following are some considerations that should be kept in mine in developing these types of studies:

1. Sample selection and collection. Materials should be sampled on the basis of what factors are to be studied.

2. Amount of material. This will vary depending on the extensiveness of the study involved. The experimental design should include a minimum of 2 replications and pot size should be 1/2 to 1 Kg. Thus, if an experiment required 10 treatments and 2 replications - 20 pots - the amount of material required would be a minimum of 10 to 20 Kg. Amount of material collected should also consider laboratory needs.

3. Type of crop.

4. Type of soil and/or plant analyses to be performed.

5. Sample preparation. Material should have a particular size where most of the material falls into the <2 mm size range. If coarse or consolidated materials are ground, it is desirable to avoid crushing too fine.

Note: Criticism has been made with respect to grinding materials for greenhouse study. However, it must be recognized that the part of the soil material that influences plant growth most significantly is the <2 mm fraction material.

6. Experiment design. Should be developed jointly by the researcher and those desiring the research to be performed.

4. <u>Field Revegetation and Stabilization Studies</u>

Field experiments are not easy to conduct and are very expensive. However, they are an absolute necessity if we are to resolve data gaps that exist for interpreting laboratory data and provide the confidence needed in developing reclamation plans.

As in the case of greenhouse and plant analyses studies, the foregoing discussion does not infer that field experimentation is always and everywhere needed for obtaining data in developing a reclamation plan. Again, this section of the report is provided to encourage, where possible,

the implementation of field investigations to provide needed and useful information.

In addition, it is hoped that a program be developed on the basis that two rather distinct activities be addressed: 1) laboratory and greenhouse research to provide basic correlation and calibration data, and 2) field experimentation to provide a mechanism for transferring laboratory and greenhouse studies into interpretations that apply to the environments where the reclamation activities are taking place.

Field experimentation needs relative to problems associated with reclamation in the western United States, as reported by various researchers include erosion, species adaptability, fertility needs, potential plant and animal toxicity, and salinity and sodium problems. Appendix I contains some useful references concerning these factors and should be reviewed to benefit from previous research efforts.

The main purpose of this section is to provide a summary of "principles of field experiments". Basically, the principles of field experimentation are as follows:

a. <u>Describing the Component Parts of the System Which Will Affect the Experiment</u>

These are:

1. Communities of plants being grown or being proposed. Choice of plants to be used could come from an assessment of current soil-vegetation relationships.

2. Soil characteristics.

3. Climatic conditions.

4. Associated biological entities - weeds, insects, diseases, and animals that might destroy plots.

5. Cultural and management practice alternatives.

b. Selection of Experimental Sites

Criteria are:

1. Uniformity - Sites must be selected where uncontrolled variables are the same over the entire experimental site, i.e., depth of soil, kind of topsoil and subsoil material, etc.. Selecting the experimental site for uniformity of uncontrolled variables will minimize experimental error and the number of replications needed.

2. Number of replications - Enough field studies have been conducted to suggest that a minimum of 4 replications per treatment are needed to minimize experimental error. Also, it is important to remember that uniformity within a plot is essential, particularly when there is variability within the entire experimental site.

c. Variables to be Studied

We should identify and define the kind and level of uncontrolled variables as well as the controlled variables. In other words, the controlled variables might be a study of the effect of various mulches in controlling erosion. Soil fertility may be an uncontrolled variable. The fertility status of the soil should be determined because it may be a limiting factor that affects response to the controlled variables. In this case, it may be desirable to apply a standard rate of fertilizer over the entire study area to eliminate this variable as a limiting factor.

d. Plot Design

Selection of a plot design is critical because different plot design techniques allow for greater or lesser precision in controlling

experimental error either by accommodating or not accommodating site variability and/or combinations of treatments. Randomized complete block and split-plot designs are most commonly used. A useful reference for determining a plot design suited for the type of experiments proposed is LeClerg et al., 1962.

In addition, plot design should consider the data analyses portion of the research. The principle types of field experiments now desired are those that will provide multiple regression analyses which relate responses to different variables and to their interactions. Field experiments should be designed for this purpose.

e. Site Protection

We recognize that the establishment of field experiments often attract animals of various kinds, i.e., gophers, rabbits, mice, deer, antelope, elk, etc.. Since field experiments are costly to establish, a site protection plan - namely fencing - is essential. Possibility of pests such as grasshoppers invading the site also must be considered.

It would appear that field experiments to evaluate existing site conditions may be useful. For example, sampling of plants as well as soil materials for laboratory analyses would provide an excellent means for evaluating the soil-plant nutrient deficiency and/or toxicity potentials that currently exist. In addition, treatment of existing soil-plant systems with fertilizer and/or soil amendments can help to indicate the nature and degree of response to treatments that may be proposed for reclaimed areas. In effect, these types of studies would provide base-line data for conditions as they currently exist, which in turn can serve as a basis for evaluating soil-plant relationships that might occur after land disturbance by mining.

In summary, field experimentation, supported by laboratory and greenhouse studies is the primary mechanism for establishing critical plant nutrient deficiency and/or toxicity criteria. The "state of the art" is inadequate for assessing many of the "data interpretive" questions being asked.

III. DATA EVALUATION AND APPLICATION

A. Geologic Overburden

From the standpoint of mine land reclamation the following questions should be addressed in mining and reclamation plans and environmental reports: What are the nature and magnitude of both the beneficial and the adverse affects resulting from the proposed surface mining activity? What actions must be taken to mitigate or minimize any possible environmental damage (adverse effects)?

Specific adverse effects that might need addressing in mining, reclamation and environmental reports include:

1. Handling of overburden rock units that are highly acidic, saline or sodic and units that contain high levels of phytotoxicants (particularly heavy metals).

2. Constitution of a suitable soil or subsoil material from overburden rock units should mining operations result in excessive disruption of marginal surface soils.

3. Final contouring of surface and reestablishment of surface drainage after backfilling operations are completed to minimize subsequent erosion and to optimize surface runoff from the mined area (Keefer and Hadley, 1976).

The geologic data base that should be available to aid in answering these questions and in recognizing and addressing these adverse effects includes:

1. Maps of the exploration area showing the surface topography and the location of boreholes, pits, roads, etc..

2. A detailed geologic map showing the types of surface materials, location of potential borrow deposits and geologic hazards.

3. Lithologic and geophysical logs of boreholes. Photographs of cores and lists of all retained cores and/or cuttings, methods used for backfilling all boreholes and pits.

4. Geologic cross-sections showing soil and rock types and rock structure within the proposed mine area.

5. Isopach maps of the topsoil, the overburden and interburden, and the host rock or coal seam. Ratios of overburden to host rock or coal seam thicknesses.

6. Structural contour maps showing the subsurface elevations of the floor of the host rock or coal seam and the subsurface elevations of major rock units that contain high levels of toxic or undesirable materials.

7. Records of all geochemical, mineralogical, and textural analyses.

8. A narrative summary of the conditions of the exploration site to include: regional geology and seismicity, surface conditions and topography, physical, mineralogical and geochemical characteristics of the overburden and interburden material, nature and extent of toxic materials present in the overburden, and geologic hazards.

It is readily apparent from a review of the literature that there is a lack of information concerning the physical and chemical characteristics of geologic overburden materials in many potential surface mine areas in the western United States such as the Fort Union region in North Dakota. Most of the overburden in this area as well as in other areas of the western United States appears to be saline and sodic shales and claystones which create severe problems in rehabilitation. Scoria, sandstone and gravel, while more desirable for rehabilitation, are also more scarce. Some of the shales and claystones might be less saline, and if so more easily rehabilitated. An inventory of these more preferred substrata

is certainly desirable and warranted (Thorne Ecological Institute, 1975).

In some surface mine areas of the western United States these types of inventories are presently under way by state and federal agencies. One particular area that has received considerable attention is west central North Dakota (Moran et al., 1978). Another such area is the Gillette area in Wyoming. The U. S. Geological Survey is gathering data on the topography, landforms, geology, coal reserves, geochemistry, surface water, erosion and sediment yield, and groundwater to ascertain the potential effects of surface mining of coal (Keefer and Hadley, 1976).

One inevitable effect of surface mining is the alteration of the surface topography as a result of surface mining operations. This alteration depends on factors such as depth and thickness of the coal being mined and the manner in which the overburden is being replaced in the mined-out pits. A cross-section showing the potential changes in topography in the Gillette area as a result of surface mining of coal is given in Fig. 13. Knowledge of the post mine landscape is especially important in areas where the strippable coal is thick in comparison to the overburden material. Such reconstructions are essential to determining the potential disruption of surface drainage and predicting changes in erosion and sediment yield patterns. Because of the thickness of the coal in this area the ground surface will be lowered considerably (Fig. 13). As a result extensive closed depressions may be created and gullying along stream course upstream from high walls and increased erosion and sediment yield may result if proper reclamation procedures are not followed.

Potential environmental problems such as those found in the North Dakota and Gillette areas can only be recognized if a sufficient data base from overburden and hydrology studies exists. Solutions to some

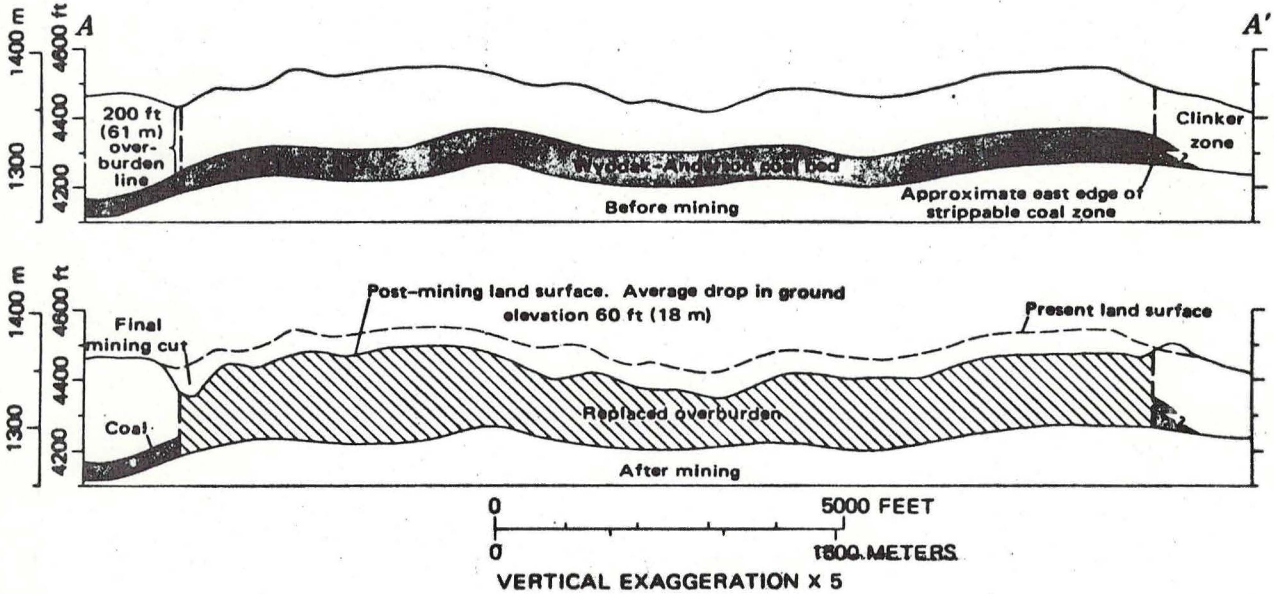


Figure 13. Cross-section showing potential changes in topography resulting from surface mining in the Gillette area, Wyoming. Lower section is based on assumption that overburden is replaced on a cut-by-cut basis with 200 ft. wide (60-m-wide) cuts, spoils are smoothly graded, high walls, are graded to a 3:1 slopes, and overburden expands 20 percent (after Keefer and Hadley, 1976, fig. 14, p. 19).

potential environmental problems must be based on a regional as well as a site-by-site basis.

B. Soil

1. Field Inventory Data Application

The field inventory maps and accompanying descriptive information will be directed toward answering the following basic question: How much soil material is available that is suitable as plant growth media and what is the distribution of these materials on the site?

The field inventory data base should include the following information for answering the above question:

1. Adequate soil profile descriptions so that topsoil, subsoil and substratum (material within 72" of surface or to depth of bedrock if the latter is less than 72") isopach maps can be developed to calculate the amount of material.

2. Soil map at a scale sufficient to portray the extent and distribution of the different kinds of soils which occur.

3. Adequate soil mapping unit description to determine the relative homogeneity of soils within a mapping unit and to provide adequate information for making land capability interpretations.

4. Interpretive classifications should be made for each soil mapping unit with regard to land capability classification, important and unique farmlands, range-site classification, erosion susceptibility and other soil and/or land classification interpretations that might be useful in developing a reclamation plan.

Most of the interpretive classifications can be developed very easily if the field data are collected using the procedures outlined in this report and the interpretation guidelines which are available from agencies

such as the Soil Conservation Service, USDA; Bureau of Reclamation, USDI; Forest Service, USDA; and Bureau of Land Management, USDI.

2. Laboratory Data Application

The major problem facing land planners, relative to use of laboratory data, is identifying data needs and interpreting the data once obtained. The diversity of management goals, controlling specifications, variability in physical and plant system environments and lack of interpretive correlation data makes this task somewhat difficult. Further, the complexity of these interrelated factors renders impractical any attempt to develop or apply uniform criteria. In addition, definable and applicable criteria are more reliable for dealing with some factors as compared to others.

This section is an attempt to present the "state of the art" in interpreting and applying laboratory data in mined-land reclamation and to provide a basis for knowing what to look for in differentiating what is important and what is not in relation to individual projects.

This section is written to present information that can be useful for evaluating and applying laboratory data to the following concerns: 1) soil fertility relationships, 2) soil salinity and/or sodium relationships, 3) soil textural relationships, 4) mineralogical relationships, 5) trace element deficiency and toxicity relationships, 6) soil erosion relationships, and 7) developing a soil and geologic overburden laboratory characterization program.

Use has been made in this section of many sources of unpublished as well as published information.

a. Soil Fertility Relationships

The uptake of nutrients by plants is one obvious criterion for assessing their availability. However, no two species of plants growing on the

same soil take up the same quantity of the various nutrients. These variations in uptake are the result of such things as pH of the soil, moisture status, overall fertility status, nature of the plant and content in the soil of the nutrients.

The above interrelationships have been resolved - at least to a satisfactory degree - for many soil-plant systems through soil test correlation research programs. Most of these investigations have, however, been carried out for agronomic crops under soil moisture regimes quite different from those in which surface mining is taking place in the western United States. And, although agronomic and/or introduced forage crops will be used in some areas in reclamation; and for which some existing soil test correlation data will be applicable, native vegetation, as well as drier soil moisture regimes, will be the more common soil-plant system for which fertility assessments are made.

Thus, the "state of the art" for evaluating potential soil fertility needs associated with most reclamation efforts is based primarily on judgement.

Data shown in Table 15 identifies the soil test-fertilizer recommendation criteria currently being used by the Colorado State University Soil Testing Laboratory. The fertility interpretations provided are thought to be those which most closely approach mined-land reclamation interpretive needs. However, it must be remembered that these relationships are based on correlation data for a given soil chemical extraction method and for specific crops. (Soil test methods are indicated in the Table.) The purpose for providing this information is not to suggest that the fertilizer treatments recommended be universally applied. This would be undesirable because the recommendations do not have regional

Table 15. FERTILIZER RECOMMENDATIONS

Nitrogen				Phosphorus		Potassium	
Small Grains							
(1) NO$_3$-N soil test ppm	Soil organic matter - % 0-1.0	1.1-2.0	>2.0	(2) Phosphorus (P) soil test ppm	Fertilizer phosphorus lbs/A P_2O_5	(3) Potassium (K) soil test ppm	Fertilizer potassium lbs/A K_2O
	Fertilizer N lbs/A						
0-6	50	40	30	0-7 low	40	0-60 low	30
7-12	30	20	10*	8-14 medium	20	>60 high	0
13-18	10*	0	0	14 high	0		
19-24	0	0	0				
> 24							

Ten lbs N is recommended only when phosphorus and/or potassium is also required.

Nitrogen				Phosphorus		Potassium	
Native and Improved Range Grasses							
NO$_3$-N soil test ppm	Soil organic matter - % 0-1.0	1.1-2.0	>2.0	Phosphorus (P) soil test ppm	Fertilizer phosphorus lbs/A P_2O_5	Potassium (K) soil test ppm	Fertilizer potassium lbs/A K_2O
	Fertilizer N lbs/A						
0-6	40	20	0	0-7 low	30	0-60 low	30
7-12	20	0	0	>7 high	0	>60 high	0
12	0	0	0				

(1) Phenoldisulfonic Acid Method

(2) Sodium Bicarbonate Extractable P levels

(3) Ammonium Acetate Extractable

The above soil test values can be interpreted only for soils tested by the respective methods listed.

Remarks

Experience and test results to date indicate that N and P are the elements most likely to be deficient in soils on mined land reclaimed areas. However, responses to fertilizers which are applied to correct these deficiencies are not always obtained because other factors such as soil moisture may be more limiting than these nutrients. The likelihood of a response to added K even at low K soil test values is probably minimal except possibly on very sandy soils.

The authors of this manual know of no available data which can be used to evaluate other nutrient deficiencies.

Below are listed critical levels at which Fe, Mn, Cu and Zn are considered to be potentially deficient for those agronomic crops which are sensitive to deficiency of these elements and in many cases for those crops grown under irrigated conditions. They cannot and should not be interpreted as being critical for most of the plants grown on most soils/spoils and soil moisture regimes in the western U. S. However, if the levels fall much below those identified below, further evaluation may be necessary.

Element	DTPA Extractable ppm (critical level)
Zn	<0.25
Fe	<2.5
Mn	<1.0
Cu	<0.2

application because of crop, climatic and soil differences. Rather, the information is provided to serve as a first approximation in attempting to identify and/or isolate potential fertility problems associated with a mined-land reclamation effort, recognizing that what might be considered a low soil P level for one type of plant may not be low for another type of plant and/or soil moisture regime.

N and P are recognized as being the most potentially limiting plant nutrients in soils of reclaimed areas in the arid and semi-arid west. However, the degree of deficiency varies greatly due to soil properties, plant type, prevailing climatic conditions, etc..

Although there is little data available, following is a summary of the present "state of the art" for evaluating the status of several other nutrients in addition to those listed in Table 15 and/or discussed in the section which follows:

Sulfur - Deficiency very unlikely to occur but usually is potentially limiting in very coarse, well-drained, low organic matter soils.

Calcium - Generally present in sufficient quantities. However, may be important from the standpoint of plant nutrition because of the ratio of Ca to Mg. When Mg exceeds Ca on an equivalent basis, plant yields may be influenced. High Mg to Ca ratios have been found for a number of geologic overburden materials. Specific criteria for evaluating this relationship are not well developed.

Boron - Deficiency, if it occurs, is probably restricted to isolated situations. Toxicities are likely to be more common than deficiencies.

Molybdenum - Because of the alkaline nature of most soils found in arid and semi-arid regions, deficiency of this element is unlikely to occur.

In summary, research is being carried out in various parts of the western United States by state, federal and private groups in an attempt to develop interpretive data for evaluating nutrient deficiencies. Thus, soil fertility evaluations can best be made through contact with persons having on-going research programs.

b. Soil Salinity and Sodium Relationships

Excessive salinity and exchangeable sodium in soil and geologic overburden are found to be problems hindering revegetation of strip-mines in many areas in the arid and semi-arid western regions. General guidelines for evaluating suitability of topsoil (A horizon), subsoil (B & C horizons) and geologic overburden for revegetation of regraded mined lands under nonirrigated conditions are given in Table 16. Since irrigation water and soil amendments can ameliorate salt and sodium conditions and present a large array of interpretive problems, the guidelines are limited to nonirrigated conditions except where salt and sodium reach "undesirable" levels. Similarly, plants have a wide range in salt tolerance characteristics which cannot even begin to be covered adequately within the purpose and intent of these guidelines. The guidelines for salinity were approached on the basis of difficulty in obtaining plant stands on saline soils under nonirrigated conditions. Most plant seeds will germinate under quite saline soil conditions but a great many will fail to emerge and, of emergence takes place, many die during the seedling stage, especially of drought conditions exist simultaneously.

The excellent to good suitability rating for soil salinity and sodium are those levels that should result in little or no difficulty in establishing stands of plants usually used for revegetation and would qualify for "prime-land" category, with respect to salinity and sodium.

Table 16. SUITABILITY OF TOPSOIL, SUBSOIL, AND OVERBURDEN FOR REVEGETATION OF REGRADED SURFACE MINES UNDER NON-IRRIGATED CONDITIONS IN ARID AND SEMIARID REGIONS.

Factor	Material	Highly Suitable (Excellent to Good)	Suitable (Fair)	Undesirable Except with Amelioration (Poor)	Amelioration
$EC_{se}x10^3$ mmhos/cm	Topsoil (A-Horizon)	<2	2-4[1]	>4[1]	Leaching to reduce to <4
ESP	Topsoil (A-Horizon	<5	5-10	>10	Amendment to reduce[2] ESP to <10
$EC_{se}x10^3$ mmhos/cm	Subsoil (B & C Horizons)[3]	<4	4-8	8	Leaching to reduce to <8
ESP	Subsoil (B & C Horizons)	<10	10-15	15-30[4]	Amendment to reduce[2] ESP to <15
ESP	Subsoil (B & C Horizons) 2:1 Swelling Clay Content >65% of <2 μ fraction	<5	5-10	10-15	Amendment to reduce[2] ESP to <10
$EC_{se}x10^3$ mmhos/cm	Overburden (B & C Horizon Contact Material)	<4	4-8	>8[1]	Leaching
ESP	Overburden (B & C Horizon Contact Material)	<10	10-15	15-30[4]	Amendment to reduce[2] ESP to <15
$EC_{se}x10^3$ and ESP	Overburden as a substitute for topsoil or subsoil (B & C Horizon)	Same EC & ESP Criteria as Topsoil and Subsoil			

[1] Changes to suitable with supplementary irrigation water having $ECx10^6$ <1000 μmhos/cm and SAR <5 or annual precipitation >18 inches.

[2] Amendment alternatives: native gypsum, commercial gypsum, commercial low-B $CaCl_2$

[3] Minimum thickness of overlying A not <6 inches (15 cm)

[4] 2:1 swelling clay content 65% of <2μ fraction - reduce to topsoil value if >65%

Also, little or no decrease in plant production after stand establishment would be expected as a result of soil salinity or exchangeable sodium. Lower levels of salt and sodium are recommended for A horizon topsoil placed on the surface. Higher salt levels can be tolerated in the lower depth because plants usually increase in salt tolerance after establishment. Lower exchangeable sodium levels are recommended for A horizon topsoil or topsoil substitute because the soil surface is critical for maintenance of good water-soil-plant relationships. It is necessary to maintain an acceptable infiltration rate to prevent excessive runoff and erosion especially on steep slopes, a 10% ESP probably will not be significant in reducing infiltration rates especially on sandy-textured soils. However, some downward movement of exchangeable sodium can be expected even in arid areas. Downward movement of exchangeable sodium can affect the permeability of subsoil layers. Also, translocation of clay can be initiated at relatively low ESP levels with rainwater. Translocation of clay would reduce the moisture retention of the surface soil and reduce the permeability of lower depths. Loss of clay from the surface layer could result in an increased wind-erosion susceptibility. Thus, the long-term effects of ESP may be more important than immediate effects.

The "fair" suitability rating for salinity levels is in the range where difficulties might be expected in establishing a stand under non-irrigated conditions and that reduced plant production might be expected, especially if agronomic species were grown. The "fair" rating for exchangeable sodium would be in the range where some adverse effects on physical properties might be expected, especially on finer-textured materials. Expected adverse effects might be reduced infiltration and permeability, reduced aggregation and increased water or wind erosion.

Migration of salt or sodium, either upward by capillarity or downward by leaching, is possible also.

The "undesirable" rating does not necessarily mean that the soil or overburden could not be used. It may be that the material represents the "best available" in some cases. However, it does mean that it would probably be necessary to develop water for irrigation and to use amelioration procedures to decrease salt and/or exchangeable sodium to levels that would ensure successful revegetation. An arbitrary upper limit of 30% exchangeable sodium was imposed. This was imposed for economic considerations since the application of amendments and leaching to dissolve the amendments is a costly and time-consuming process. For example, about 1.7 tons of gypsum (100% purity) per acre are necessary to reduce exchangeable sodium by 1 milliequivalent/100 grams in a one-foot depth of soil. On the average, it will require that about a 1 to 1.4 foot depth of water be applied per acre to dissolve the 1.7 tons of gypsum so that calcium can replace sodium. An amendment, such as calcium chloride, is much more soluble but it is also much more expensive than gypsum. The water requirement for leaching of soil salts alone is usually much lower than for dissolving an amendment.

As with other aspects of strip-mine reclamation, considerable site-specific judgement needs to be exercised.

c. Soil and Geological Overburden Textural Relationships

Texture is an important soil property to evaluate in surface mine reclamation planning. In general, texture should not be examined from the standpoint of sand, silt, and clay distribution, per se, but the evaluation should be based upon several important properties that are closely related to texture. A list of factors affected by or related to

texture are given in Table 17. A generalized rating for each property is given for each textural calss. Textures most suitable or amenable to reclamation and revegetation generally fall between the sandy loam to clay loam textures. However, a primary consideration should also be maintenance of the integrity of the soil profile developed under natural conditions in so far as possible. Thus, criteria for determination of suitability with respect to texture is largely "site-specific" and rigid guidelines cannot easily be made. It is suggested that an attempt be made to rank order properties of different materials that are available according to relative importance for a specific climatic and topographical setting and assign a score to each textural class available as topsoil, subsoil, or overburden to arrive at a total quantitative score for each material available. The material with the highest quantitative score would be considered as most suitable at that specific site. Properties to evaluate include infiltration, permeability, structures, water holding capacity, stoniness, salt and exchangeable sodium, surface crusting susceptibility, wind and water erosion susceptibility, fertility, and possibly others. Salt and exchangeable sodium ratings and erosion equations are discussed in another section. The amount of different materials available for regrading or soil reconstruction is also an important factor to be considered. Qualitative suitability ratings of several factors were used by McKall and Associates (1978) to obtain an overall rating of soil suitability for strip mine rehabilitation.

The "slaking test" (Table 14) is used to evaluate consolidated overburden as a potential soil substitute material. If 65% or more of the consolidated core sample passes through a 5-mm sieve opening after being wet under vacuum and then shaken for 15 minutes in a horizontal shaker,

Table 17.

GENERALIZED RATING OF FACTORS PROBABLY NEEDING ASSESSMENT IN SURFACE MINE RECLAMATION AS AFFECTED BY TEXTURE OF SOIL OR OVERBURDEN.

Factors Affected by Texture	s	ls	lfs	sl	fsl	vfsl	l	scl	sicl	cl	sc	sic	c
1. Water Infiltration	rapid	rapid	rapid	mod. rapid	mod. rapid	moderate	moderate	mod. slow	mod. slow	mod. slow	slow	slow	very slow
2. Moisture Retention	very low	very low	very low	low	low	moderate	moderate	mod. high	mod. high	mod. high	high	high	very high
3. Potential for Water Table Aggregate Formation from Dispersed Material	very low	very low	low	low	low	low	moderate	moderate	low	high	high	moderate	high
4. Sodium Dispersion Susceptibility	very low	very low	low	low	low	moderate	moderate	moderate	high	high	high	very high	very high
5. Tendency for Crust Formation on Soil Surface	very low	very low	very low	low	low	moderate	moderate	moderate	high	high	high	very high	very high
6. Wind Erosion Susceptibility	high[1]	mod. high[1]	mod. high	mod. low	moderate	mod. high	low	mod. low	low	low	mod. low	low	low
7. Water Erosion Susceptibility	very low	very low	low	low	low	moderate	moderate	moderate	high	high	high	very high	very high
8. Aeration	very good	very good	good	good	good	good	good	good	fair	fair	fair	poor	poor
9. Inherent Fertility	low	low	low	moderate	moderate	moderate	moderate	high	high	high	very high	very high	very high
10. Fertilizer Retention	low	low	low	moderate	moderate	moderate	moderate	high	high	high	very high	very high	very high
11. General Productivity	mod. low	mod. low	mod. to high	mod. to high	mod. to high	mod. to high	mod. to high	mpd. to high	mod. low	mod. low	mod. low	mod. low	low

[1]very fine, fine, and medium sands and dune sand

it can be considered that the strata will weather rapidly and be suitable as plant growth media. The infiltration and/or permeability of soil and overburden materials after disturbance are difficult to predict except on a general basis of texture or to measure after regrading. It is expected that infiltration and permeability of soil materials will be higher than measured values in the field after regrading but will gradually decrease until they approach the value obtained before disturbance. Laboratory measurements of "hydraulic conductivity" (Table 14) probably represent the best approach for screening different textured overburden materials. The "shrink-swell" test (Table 14) should provide additional information for evaluating expected permeability changes under saturated conditions.

The following general rules can be applied in relation to other texturally related properties. Field capacity gravimetric moisture content can be closely estimated as: 1/2 paste saturation, %. Volumetric field capacity can be estimated as: gravimetric moisture, % times bulk density. Wilting point can be estimated as: 1/4 paste saturation, %. The difference between field capacity moisture content and wilting point can be used as an estimate of "plant available water".

Better plant stands, more vigorous growth, and higher production of plant material are normally obtained on A horizon topsoil if it is not mixed with subsoil layers or overburden. Germination and emergence of vegetation is usually better on a coarse-textured A horizon than on a structureless fine-textured A horizon, unless moisture is very limiting. Fine-textured materials have a greater tendency to form surface crusts which decrease the emergence of seedlings.

In general, a fine-textured A horizon should be stripped and stockpiled spearately from finer-textured textural B and/or C horizons even though the A horizon is relatively thin. Mixing a textural B horizon (B_2t) with a fine-textured A horizon, for example a clay loam, is apt to markedly decrease water infiltration and increase erosion. However, mixing a textural B horizon with a greater or equal amount of sandy A horizon usually will not decrease infiltration to seriously low rates and may be beneficial by increasing moisture retention capacity.

Other considerations with respect to soil profile reconstruction during regrading operations are as follows. In general, a coarser-textured A horizon placed over a finer-textured subsoil is more suitable for promoting surface infiltration and for maximizing moisture storage while reducing surface runoff and erosion. Placing materials with a large textural difference over one another is undesirable, especially fine-textured material over coarse-textured material, because it acts to interrupt downward moisture flow and creates "perched water tables". Compacted zones should be eliminated when placing one material over another because compaction impedes moisture flow.

Illustrations of regrading operations, seed bed preparation, and various erosion control techniques are shown in publications by Mills and Clar (1976) and Soil Conservation Service (1977).

d. Mineralogical Relationships

Pyrite mineralogy - Pyrite (FeS_2), formed in overburden materials under reducing conditions, oxidizes to form sulfuric acid when exposed to atmospheric oxygen or oxygenated waters. The rate of this reaction is increased as the particle size of the pyrite decreases and in the presence of sulfur-oxidizing bacteria (species of *Thiobacillus*).

Framboidal pyrite, a fine-grained pyrite occurring in aggregates of individual crystals,usually <2 microns in size, oxidizes rapidly whereas large crystals react slowly. The overall reaction is shown in Equation 1 below. When soil and overburden contains alkaline earth carbonates, such as lime, the acidity produced by pyrite is neutralized as shown in Equation 2.

$$2FeS_2 + 7\text{-}1/2\ O_2 + 4H_2O \rightarrow 4H_2SO_4 + Fe_2O_3 \qquad (1)$$

$$H_2SO_4 + CaCO_3 \rightarrow Ca^{++} + SO_4^{=} + CO_2 + H_2O \qquad (2)$$

Pyrite is detected in overburden materials by the qualitative method of Neckers and Walker (1952). The total acid potential of pyrite-bearing strata is quantitatively determined by analysis for total sulfur (Smith et al., 1976) from which gypsum and water soluble sulfates are subtracted. The acid neutralization potential is determined on the basis of the overburden lime content. An "acid-base account" procedure (Smith et al., 1976) is used to determine whether sufficient lime is present to neutralize the total potential acidity. Thus, pyrite in overburden materials should not be present in amounts sufficient to produce acid soil and acid drainage water if overburden is used as a soil substitute or is in contact with regraded subsoil. Prevention of acid soil formation is especially important because heavy metals, in general, become more available to plants and heavy metal concentrations increase in groundwater as the soil becomes more acidic. Also, if the sulfuric acid produced by pyrite-oxidation is neutralized by lime, this can result in detrimental effects on groundwater by raising the salinity content as soluble calcium and sulfate ions.

Clay mineralogy - Swelling or expanding (2:1 type) clay minerals in soils and geologic overburden with excessive absorbed sodium undergo dispersion and decrease soil permeability to a greater degree than non-swelling clays. Identification and quantification of the less than 2 micron clay mineral fraction could be used as an additional criteria for determining critical exchangeable sodium levels. If the soil clay contains more than 65% 2:1 lattice swelling clays, lower limits of ESP could be imposed for the particular suitability class. Clay mineral analysis can be helpful in determining the suitability of overburden as a soil substitute. Overburden with a combination of both nonswelling and swelling clays would be preferable for soil profile reconstruction.

It is recommended that clay mineral analyses be run on only a few cores per site. Lateral variation in the clay mineral suite is generally not great within the area of a proposed surface mine. The possibility exists for greater vertical variation within different depositional strata or rock formations.

Sandstone mineralogy - Microscopic examination of thin section samples of sandstone overburden units, although not a common practice, can provide useful data to aid in the correlation of overburden strata and to supplement other physical and chemical data on the friability, resistance to mechanical breakdown, weatherability and pyrite content of these units. Little work has been completed on the petrographic characteristics of overburden in the western states. Studies of the mineralogical and textural characteristics and weatherability of Eocene (Wasatch) sandstones of the Powder River Basin, Wyoming, are presently under way by the authors of this report. In the eastern United States, petrographic studies of Pennsylvanian Age Sandstones by Grube et al., (1972) have

revealed that some aspects of geologic overburden that are important to mine land reclamation.

Petrographic studies of the Lower Mahoning sandstone, coupled with determination of the total sulfur content of pulverized samples revealed sufficient pyrite free rock material to place in the oxidation zone of spoil heaps to avoid acid pollution. However, these studies also reveal abundant sandstone at depths below 6 meters that contain highly toxic materials that would produce prolonged sources of acid water pollution unless protected from oxidation by deep burial or other means (Grube et al., 1972).

Petrographic studies of the material filling the pore spaces between framework grains of sandstones revealed moderately calcareous sandstones while hard at the time of excavation will break down relatively rapidly when left near the surface so that circulating waters are able to remove the carbonate cement. Sandstones with argillaceous parting and clay matrix may also be hard at the time of excavation but will disentigrate rapidly near the surface. The argillaceous sandstones are particularly useful where additional sand would be beneficial in the soil (Smith et al., 1974).

e. Trace Element Toxicity Relationships

Zinc and iron were considered in a general way from the standpoint of deficiency to plants in section a. These same elements, with the exception of iron, as well as other trace elements - some of which are necessary for plant growth and others which are not - are discussed further in this section because of their environmental importance. In addition to some of these elements being important as required plant nutrients, they are also of concern from the standpoint of toxicity to plants, animals and man.

The trace elements considered in this section do not include all elements having potential impact on the environment. Those included are recognized as perhaps being the most important and/or likely to be a problem. In general, interest in trace elements tends to be based on the following:

1. Those that are toxic to plants and/or animals (boron, selenium, and molybdenum).

2. Those that are toxic to fish (zinc).

3. Those that are toxic to man and animals (selenium, arsenic, cadmium and nickel).

This is not to say that other elements may not be or importance. However, those listed are of highest interest and, in general, may be the most likely to occur in quantities in available forms to plants and animals to cause problems.

Evaluation of potential trace element problems is complicated by the same sets of factors as those we find associated in soil fertility evaluations. Although plant uptake of these metals is one criterion for assessing their effects, different plants take up different quantities and the availability of these elements to plants and their mobility in environment is controlled by soil pH, drainage, moisture regime, and amount present in the soil. Also, nutrient interactions within the plant and/or animal control whether or not deficiency and/or toxicity may occur. Toxicity levels for plants, animals and in soils have been reported for some elements while critical levels for other elements have not yet been established.

Evaluation of trace element and plant nutrient relationships for geologic overburden is further complicated by the fact that if the deeply

buried materials, that are relatively unaltered, are brought closer to the surface and subjected to the natural bio-geochemical weathering process, significant changes may occur in their chemical and physical properties through time. These changes may not be identifiable either through "total" or "available" chemical analysis performed on fresh materials.

Geologic material identification through mineralogical analyses can be a useful tool for identifying minerals having weathering reaction products that might be significant to the plant-soil-water environments. If mineralogical analyses are not performed, then other measures are needed to identify potential changes in geologic materials as a result of weathering, i.e., long term leaching effects and plant growth and plant tissue analyses.

It appears that a logical approach to the problem at the present time is to 1) know something about the kinds of soil or geologic materials in which these elements are likely to occur in high amounts and 2) make some arbitrary assessment as to the availability of these elements to plants and/or animals based on an interpretation of the soil systems that occur or are likely to occur on the site, and 3) if a problem is suspected, make an appropriate choice of a chemical extractant which will indicate the potential availability to plants and/or mobility of the element in the bio-geochemical environment.

The data provided in Table 18 shows, in general, the amounts of some trace elements found in rocks that form soil parent materials. This information enables us to anticipate with some degree of confidence the approximate amount of a trace element that might be present if we identify the nature of the geologic material(s) with which we are working.

Table 18. GENERAL RELATIONSHIPS OF OCCURRENCE AND AVAILABILITY OF TRACE ELEMENTS IN SOIL AND/OR GEOLOGIC OVERBURDEN

GENERAL ABUNDANCE AND OCCURRENCE OF TRACE ELEMENTS IN GEOLOGIC AND SOIL MATERIALS IN ppm (Bowen, 1966; Swain, 1955; Taylor, 1961) (Total Concentration)

	Mn	B	Zn	Cu	As	Pb	Mo	Se	Cd	Ni
Earth crust	950	10	70	55	1.8	12.5	1.5	0.05	0.2	75
Sedimentary rocks										
Shale	850	100	95	45	13.0	20.0	2.6	0.60	0.30	68
Sandstone	50	35	16	5	1.0	7.0	0.20	0.05	0.05	2
Limestone	1100	20	20	4	1.0	9.0	0.4	0.08	0.035	20
Soils										
Range	100-4000	2-100	10-300	2-100	1.0-50	2.0-200	0.2-5.0	0.01-2.00	0.01-7.00	--
Mean	850	10	50	20	6.0	10.0	1.0	.20	0.06	40

Concentrations of trace elements in the surface layers of soils in Powder River Basin - in ppm (after Keefer and Hadley, 1976)

	Mn	B	Zn	Cu	As	Pb	Mo	Se	Cd	Ni
Depth 0-1 inch (0-2.5 cm)										
Range	70-1000	<2.0-70	28-93	3-30	--	10-30	<3-20	--	--	<5-30
Mean	280	31	62	16	7.2	18	--	0.20	--	15
Depth 6-8 inches (15-20 cm)										
Range	100-700	<20-70	25-104	5-50	--	10-100	<3-5	--	--	<7-50
Mean	250	28	64	18	8.2	18	--	0.14	--	16

*Providing specific criteria for evaluating potential toxicity and/or deficiency of these elements is impractical and even dangerous because of the variability in tolerance to these elements by different plants, even within the same species--animals and man. The only appropriate manner for handling these questions at the present time is to review recent literature and determine if data that are available actually apply to a particular situation. Suggested references are: Chapman et al 1966, Mitchell 1964, Connor et al 1975, Cannon et al 1972, Shacklette 1972, Hemphill 1973, Prabhakarannair 1969, Connor et al 1976, Cragg 1971, Norman et al 1968.

GENERAL SOIL CONDITIONS WHERE ELEMENTS ARE MOBILE OR AVAILABLE TO PLANTS

Element	Soil Condition	Remarks*
Mn	most available under acid soil conditions; neutral or alkaline soil conditions may cause deficiencies	Manganese toxicities in plants generally occur on very acid soils. Deficiencies may occur on neutral or alkaline soils. Excess Mn may restrict plant growth.
B	low precipitation, alkaline soil conditions	Boron toxicity can occur in arid areas where sodium and calcium borates occur in soils. The safe limits of available Boron content between deficiency and toxicity are narrow.
Zn	soil low in $CaCO_3$; acid soil conditions	Zinc toxicities can occur on acid soils that are heavily fertilized with zinc fertilizers. Zinc tends to accumulate at or near the surface of the soil.
Cu	acid soil conditions	Deficiency of copper occurs on sandy alkaline soils that have been well leached. Toxicity of copper can occur on soils that have been subject to applications of sprays containing copper.
As	alkaline soil conditions	No evidence that arsenic is essential for plant growth. Toxicity generally occurs in areas that have accumulated arsenic in the soils through foliar spray compounds.
Pb	acid soil conditions	Lead accumulated in surface horizons of many soils does not appear to be readily available to plants. Lead may be absorbed by plants from pollution and then be toxic to animals.
Mo	wet soils and neutral to alkaline soil conditions	Heavy applications of phosphatic fertilizers will increase molybdenum uptake by plants. Excessive amounts of molybdenum are toxic to grazing animals.
Se	alkaline soil conditions with well oxidized environment	Selective plants such as Astragalus and Sium genera accumulate selenium and may cause poisoning in grazers. Associated with sedimentary rocks.
Cd	mildly alkaline to acid soil conditions	Not usually toxic to plants. Cadimum may be absorbed by plants from pollution and may cause toxicity to grazing animals.
Ni	acid soil conditions	Non-essential for plants and animals. The amount of nickel absorbed ranges widely among species.

In addition, the data in Table 18 identifies the soil conditions in which the various trace elements may be potentially more available to plants and also more mobile in the soil and thus subject to leaching.

f. Soil Erosion Relationships

Following are described some accepted procedures for evaluating wind and water erosion potential and which identifies regraded and stockpile areas.

The methods discussed have certain limitations and it is suggested that the references listed be carefully reviewed to ensure that the methods are not misinterpreted relative to their applicability for assessing erosion for a given condition. The procedures outlined can be an excellent tool for assessing the relative erosion potential that might exist, but must be used with discrimination and with adequate background information relative to the values that are used for assessing the impact of a particular variable.

Wind Erosion - Overall susceptibility to wind erosion has been demonstrated to be the result of a number of variables and has been expressed in the form of the equation

$$E = f(I\ K\ C\ L\ V)$$

E = the predicted average annual soil loss expressed in tons/acre/year.

I = soil erodibility. This is the inherent potential of the soil to erode under a "bare" surface condition.

K = a soil surface roughness factor. Many times, roughening of the soil surface by mechanical means can, on some soils, completely stop wind erosion for at least a short term period. This factor should be seriously considered as a "short term" practice as part of an erosion control plan. Guides are available for

calculating surface roughness for specific site situations. This practice would be most useful on soils having "moderate" wind erosion susceptibility because they generally leave a cloddy as well as roughed surface condition after treatment, both of which are effective in controlling wind erosion.

C = climatic factor. THis factor is evaluated based on the average wind velocity and on the precipitation-evaporation index for a given area.

L = The unsheltered distance along the prevailing wind direction. Attempts should be made to avoid creating unsheltered or bare soil areas which are moist subject to prevailing winds. For example, creating a bare area on the windward side of a knoll greatly increases susceptibility to wind erosion and stabilization procedures would have to recognize this situation if it exists. Otherwise, stabilization efforts often will fail.

V = vegetative cover. This variable in wind erosion evaluation considers three conditions: 1) quantity of residue, 2) kind of residue, and 3) the orientation of the residue.

Water Erosion - Factors important for evaluating water erosion potential and a basis for developing erosion control management practices have also been combined in the form of the following equation-like expression:

$$A = R\ K\ L\ S\ C\ P$$

where

A = computed soil loss expressed in tons/acre/year.

R = the rainfall factor. An index which is the measure of the erosive force of specific rainfall. This value can be expressed as a mean over an annual period or for short periods of time.

K = the soil erodibility factor. A relative value expressed from 0 to 1.0 which reflects the inherent potential of soil to erode by water when exposed.

LS = slope length and degree factor.

C = crop cover or management factor.

P = erosion control practice factor such as contouring, terracing, etc..

Numerical values for each of the six factors have been determined from field experience and research data. Values for use in the wind erosion equation also are available (Soil Conservation Service, 1977a,b,c).

g. Developing a Soil and Geologic Overburden Laboratory Characterization Program

The main objective in developing a soil and geologic overburden laboratory characterization program is to avoid mass sample characterization by minimizing the number and/or kinds of analyses that are performed. This is done without sacrificing quality and kinds of data needed for making the assessments necessary.

The Bureau of Reclamation, USDI, has for many years based the level and intensity of laboraotry characterization on an approach called "screenable soil characterization as related to land reclamation" (personal contact, Mr. Richard Piper, USBR, Denver, CO). In screenable characterization a multi-phase program is developed which minimizes the number and kinds of analyses to be performed. This approach emphasizes that the number and types of laboratory studies to be carried out will be determined by area conditions, particularly variability of soils and land types, and the controlling specifications and needs. Thus, the laboratory characterization must be coordinated from the very beginning with the field investigations. Using this concept, the information in

Table 19 was developed as an example for determining data needs for evaluating soil and/or geologic overburden material as plant growth media and effects on environmental quality. The approach as presented in Table 19 may require modification based on present federal, state and local regulations as well as particular site characteristics. It does, however, provide a basic framework for developing a data needs plan.

C. Interpretation and Application of Ground and Surface Water Data

The interpretation and uses of ground and surface water data relative to surface mining are highly site specific. Here it is possible to provide only general guidelines and procedures.

1. Surface and Ground Water Quality

An important purpose of collecting data on the quality of surface and ground waters is to provide a baseline from which changes attributable to mining can be detected. For purposes of pre-mine planning and decision making, however, it is necessary to identify and understand, quantitatively, the role that the study site plays in determining the quality of waters used internal and external to the study site. Only then is it possible to rationally project potential changes caused by the mining operations. There are a number of specific steps that must be accomplished.

A first step is to combine the water quality data with the estimated discharges of ground and surface waters to determine chemical discharge from the site to potential receiving waters. The chemical discharge can be computed in terms of specific ions of particular concern, in terms of total dissolved solids, or both. Knowledge of the quality and discharge of the receiving waters below the points of inflow from the study site assist in determining the contribution from the study area. The framework in which the analysis is applied is that of a combined expression

Table 19. Example of an Approach for Determining Interpretative Data Needs

Situation	Data Needs
	A. Soil Resources
1. Identify current soil resource status.	
a. Important and prime farmlands.	a. Federal Register (Jan. 31, 1978) and any state criteria available through the Soil Conservation Service.
b. Land capability.	b. Identify management practices needed to maintain or increase productivity by utilizing existing soil and land interpretive classifications utilized by the SCS, USBR, and other agencies.
2. Determine plant growth media potential of given soil resource.	a. Soil isopach maps developed from soil inventory are used to determine distributions and extent of soil materials. b. Laboratory analyses needed to determine quality of soil resources: salinity, sodium, pH, organic matter, texture, available N, P & K, percent calcium carbonate, percent saturation (water). Other laboratory analyses for trace elements or heavy metals in the soil should be considered dependent on type of material and in which soil has developed and the chemical status of existing soil systems. Table 18 shows normal levels in rock and soils. This will aid in determining whether or not particular elements may be suspect.
3. Determine current and potential erosion.	Variables for determining wind and water erosion should be identified (Soil Conservation Service, 1977a,b,c).
	B. Geologic Overburden Resources
4. Evaluate geologic overburden for plant growth media. (This step would be carried out if the soil resource evaluation indicates that it is necessary to utilize these materials as plant growth media.)	a. Identify distribution and extent of geologic strata from lithological core data. Sampling according to variances as shown by lithyological core characterizatio b. Laboratory analyses of select geologic overburden to determine quality as a plant growth media: salinity, sodium, pH, organic matter, texture, available N & P, pyrite, percent saturation (water), percent calcium carbonate, percent gypsum, erosion potential.
5. Evaluate geologic overburden for environmental concerns such as placement effects on ground water quality.	Select geologic overburden to determine effect on environmental quality: salinity, sodium, pH, organic matter, pyrite, percent calcium carbonate, percent gypsum. Additional analyses for other factors such as heavy metals can initially be determined based on the data shown in Table 18.

for water and chemical mass balance (Rowe and McWhorter, 1978; Kunkle, 1965; Pinder and Jones, 1969; Visocky, 1970). It is sometimes possible to refine estimates of surface and ground water inflow to the receiving waters by this procedure. For example, suppose the discharge and total dissolved solids (TDS) concentration are measured at both ends of a stream reach receiving ground and surface water inflows from the area of concern. The measured gain of water over the reach must be accountable by surface and ground water inflows, taking into account such factors as diversions, evaporation and transpiration. Similarly, the measured gain in chemical discharge (TDS multiplied by water discharge) must be accountable by chemical discharge from surface and ground water inflows. Ideally, an overall balance of both water and chemical discharge should be achieved. This is rarely possible without making reasonable adjustments of contributing factors. Often it is advantageous to perform such analyses for selected sub areas and reaches of receiving waters and over selected time intervals when one or more contributing factors can be set to zero.

Once a satisfactory water and chemical balance has been achieved, the investigator is in a position to predict how the quality and quantity of the receiving waters will be changed by changes in the quality and quantity of inflow from the study area. At this point it is necessary to estimate the changes that can reasonably be expected to occur as the result of mining. Among the factors that must be considered are changes in recharge as a result of mining, interception of surface and ground water by the pit, changes in evapotranspiration, modifications of the routes and quantities of surface runoff and the pick up of additional contaminants.

Accurately predicting such changes is difficult and only some very general guidelines can be provided. Discussion of potential changes in the quantities of recharge, ground and surface water runoff, and evapotranspiration are contained in the next subsection. The following is a brief presentation of one method for estimating post-mining quality of combined surface and ground water runoff.

The disturbance of the naturally occurring sequence of strata exposes fresh surfaces for contact by water and, therefore, enhances the opportunity for water to pick up additional soluble materials. Experience at one site in Colorado showed that the TDS concentration (as indicated by electrical conductivity) in water that had passed through the spoils was about equal to that in extracts from saturated samples of the spoil (Rowe and McWhorter, 1978). Other experience in Montana and North Dakota has not verified the equality of these measurements, however. The present state of knowledge seems to support only the rough rule of thumb that the dissolved solids concentration in spoil water will be on the order of 1 to 3 times the concentration in extracts from saturated pastes prepared from the overburden (Rowe and McWhorter, 1978; Van Voase, 1978).

In general, the quality (with respect to dissolved solids) of overland flow from disturbed lands is not greatly different from that in the undisturbed state (Rowe and McWhorter, 1978). This is particularly true if existing top soil is replaced on the spoils following mining. Apparently, pick up of dissolved solids by overland flow is not as great as for subsurface flows because the thin layer of material in contact with overland flow is rapidly leached and, because of smaller contact times, among other reasons.

Rowe and McWhorter (1978) present a simple model based upon the concepts of mass balance described in the foregoing paragraphs that may be useful for making rough estimates of the anticipated effect of mining on the TDS in combined surface and ground water runoff. Their model is

$$P_t = \frac{KR\ f_{sn}P_{sn} + (1-f_{sn})P_{gn} + f_{sm}P_{sm} + (1-f_{sm})P_{gm}}{1 + KR}$$

where

P_t = the mean TDS in combined surface and groundwater runoff from the total watershed comprised of both mined and natural lands.

K = The ratio of total drainage per unit area (including both surface and ground water runoff) on the undisturbed portion of the watershed to the total drainage per unit area from the mined land.

R = The ratio of the area of undisturbed land to the area disrupted by mining.

P_{sm} = mean TDS concentration in surface runoff from the mined area.

P_{gm} = mean TDS concentration in ground water runoff from the mined area.

f_{sm} = the fraction of total drainage from mined area that is overland flow.

P_{sn} = mean TDS concentration in surface runoff from the natural area of the watershed.

P_{gn} = mean TDS concentration in ground water runoff from the natural area of the water shed.

f_{sn} = the fraction of total drainage from the natural area that is overland flow.

This model is based on the assumption of zero net change in watershed storage and, therefore, all parameters represent means over a period for

which this assumption is approximately true. A minimum of one year is recommended.

A brief example follows. Suppose that pre-mine monitoring of the quality and quantity of ground and surface water flows on the watershed to be mined yielded P_{sn} = 210 mg/l, P_{gn} = 900 mg/l, and that f_{sn} = 0.10. Also, saturation extracts prepared from overburden samples exhibited a mean TDS of 2300 mg/l, from which it is estimated that the TDS of ground water in the spoils will be 4600 mg/l. Thus, P_{gm} = 4600 mg/l. Topsoiling is planned so it is reasonable to assume $P_{sm} = P_{sn}$ = 210 mg/l. Reclamation plans call for revegetation that can be expected to be about equal to the pre-mining vegetation. Grading of the mined lands is not expected to reproduce the pre-mining drainage patterns, however. Numerous small basins with no outlet are formed and this causes reduced surface runoff, longer surface retention of water and increased infiltration opportunity relative to undisturbed land. Thus, it is anticipated that total combined surface and ground water runoff from the mined land will be reduced relative to the undisturbed area by 15 percent. This yields K = 1/0.85 = 1.18. The difference is accounted for by increased transpiration by plants due to the increased quantity of water available in the root zone. Also, because of the lack of good surface drainage on the regraded mined land, it is estimated that the fraction of total drainage from the mined land that is overland flow will be reduced relative to the natural condition. Therefore, f_{sm} is set equal to 0.05. Finally, the mining plans call for 22 percent of the watershed to be mined. This yields R = 0.78/0.22 = 3.55.

Values for all of the parameters on the right side of the equation are now available. Substituting and carrying out the computations yields

P_t = 1515 mg/l. This is the anticipated post-mining value for the mean annual, discharge weighted, TDS concentration in total drainage from the watershed in which the mine is located. The corresponding pre-mining value is 831 mg/l. In this case, mining 22 percent of the watershed nearly doubles the mean TDS concentration in the watershed drainage.

The foregoing is a demonstration of one way in which water quality and overburden data can be utilized in pre-mine planning and decision making. The model is not applicable in all cases, of course, and other analysis procedures may be required for particular studies.

Water quality data is sometimes very useful for assisting in the understanding of the subsurface hydrologic system. For example, the proportion of surface water and ground water in the discharge of a pumping well can sometimes be determined by knowing the quality of the surface water, the quality of the unmixed ground water and the quality and discharge of the mixture from the well (Hem. 1970). Sudden changes in water quality during a pumping test can sometimes be interpreted as contributions from different zones with dissimilar water quality. Water quality in different zones may provide insight into the degree of interconnection between adjacent aquifer zones, as another example.

2. Piezometric Surface Maps and Fluctuations

Ground water level data from a network of observation wells can be used to construct piezometric surface and water table maps. Such maps are prepared by connecting points of equal water level elevation to form a pattern of contours similar to those on a topographic map. These maps provide information concerning ground water flow direction, quantities of flow (when combined with transmissivity), and likely areas of recharge and discharge. Geologic information on stratigraphy, structure, faults,

etc. should be fully utilized during the preparation and interpretation of piezometric surface maps.

An important use of such maps is to compute the quantities of ground water entering and leaving the study area, or possibly, to and from surface water bodies. These quantities are required for use in the water and chemical mass balances discussed in the previous subsection. Pre-mining flow patterns, displayed as a piezometric map are an aid to the determination of inflow to the mining pit, the estimation of the area over which the piezometric surface can be expected to be disturbed in both the mining and post-mining phases, and the post-mining flow pattern. The elevation of water levels in wells relative to the elevation of streams, ponds, springs, etc. often provides the most significant information available concerning the interrelationships between surface and ground waters. Similarly, relative elevation of water levels in different aquifers at the same location provides information on the degree of hydraulic interconnection between aquifers, especially when one of the aquifers is being pumped.

Figure 14 is an example of a piezometric surface map prepared for and overburden aquifer at a potential mine site. The direction of ground water flow is toward the northeast in this case. Comparison of piezometric surface elevations in the potential mine area with those in a shallow alluvial aquifer adjacent to the site on the east and north sides indicated that ground water discharged from the potential mine site into the alluvial aquifer. The gradient (slope) of the piezometric surface as about 0.006. This data, together with measured values for transmissivity of 7×10^{-3} ft^2 per min and the area through which flow is occurring yields an estimated 5.4 acre-ft/yr of ground water discharge into the alluvial aquifer.

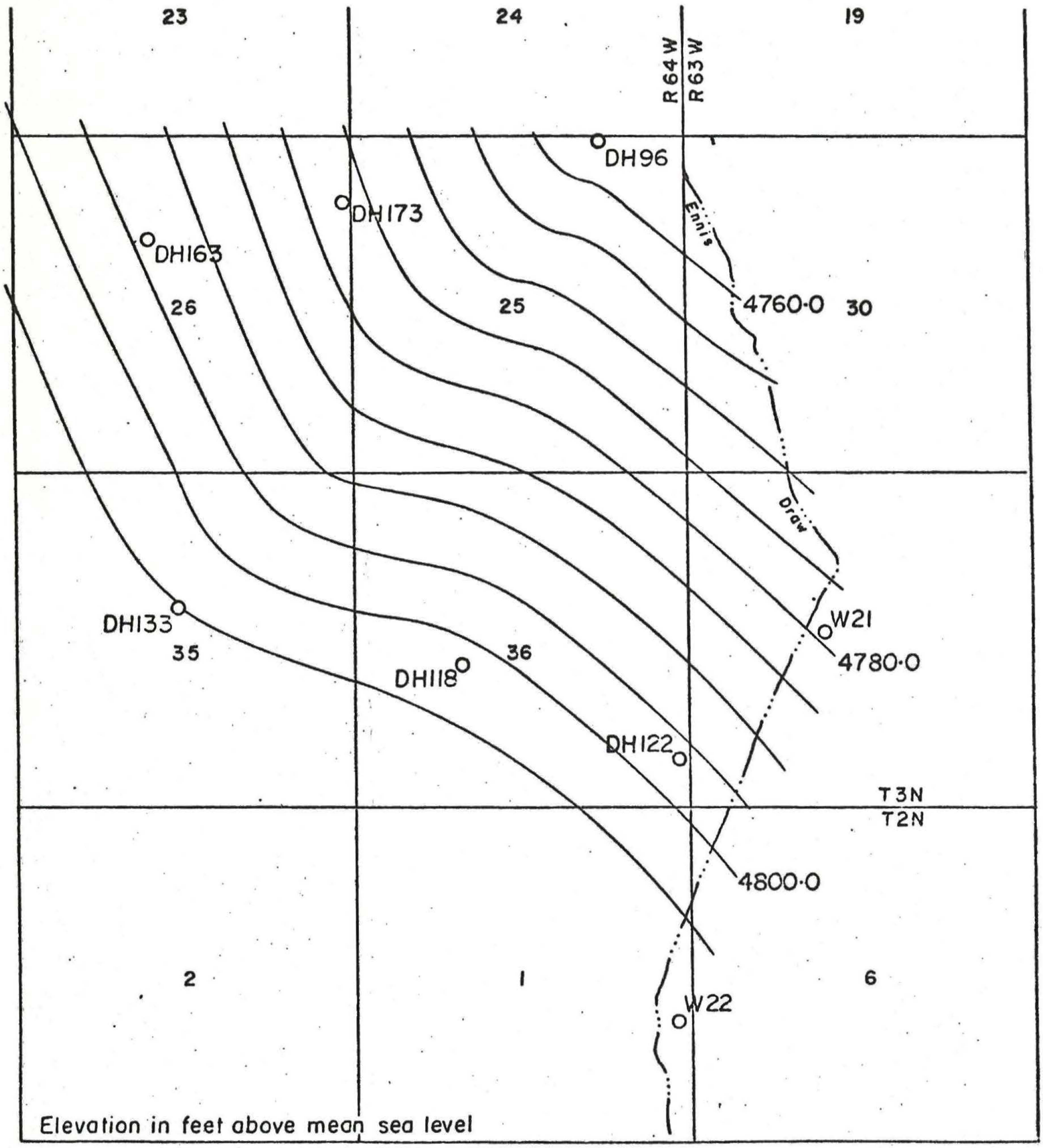


Figure 14. Piezometric surface of overburden aquifer in October, 1978.

Knowledge of the quality of the ground water in the overburden aquifer and the alluvial aquifer permits the estimation of the influence of the overburden waters on both the quantity and quality of the waters contained in the alluvial aquifer.

Water level fluctuations can sometimes be used to estimate recharge when values for the storage coefficient or apparent specific yield are known. Multiplying the observed change in water level by the storage coefficient or the apparent specific yield gives the volume of water per unit area that has been added or removed from the aquifer. Factors other than recharge and discharge sometimes cause water levels in wells to fluctuate, however. Barometric pressure changes often cause water levels in wells penetrating confined aquifers to change by as much as several centimeters. Water levels should be correlated with barometric pressure and precipitation to help assure a correct interpretation.

Figure 15 shows measured water levels in three wells in a potential mine site. The fluctuations apparent in the lower two graphs correlate well with each other, and these short term fluctuations represent response to atmospheric pressure fluctuations indicating that both wells are completed in a confined aquifer. The upper graph shows the water level in a well penetrating an unconfined aquifer in the same area. The conclusions drawn from these records was substantiated by geophysical and geological data at the site. The time period over which these data were collected is too short to draw any conclusions concerning the indicated trends relative to recharge or discharge. Nevertheless, this example demonstrates how water level fluctuation data can assist in the interpretation of geologic and geophysical information.

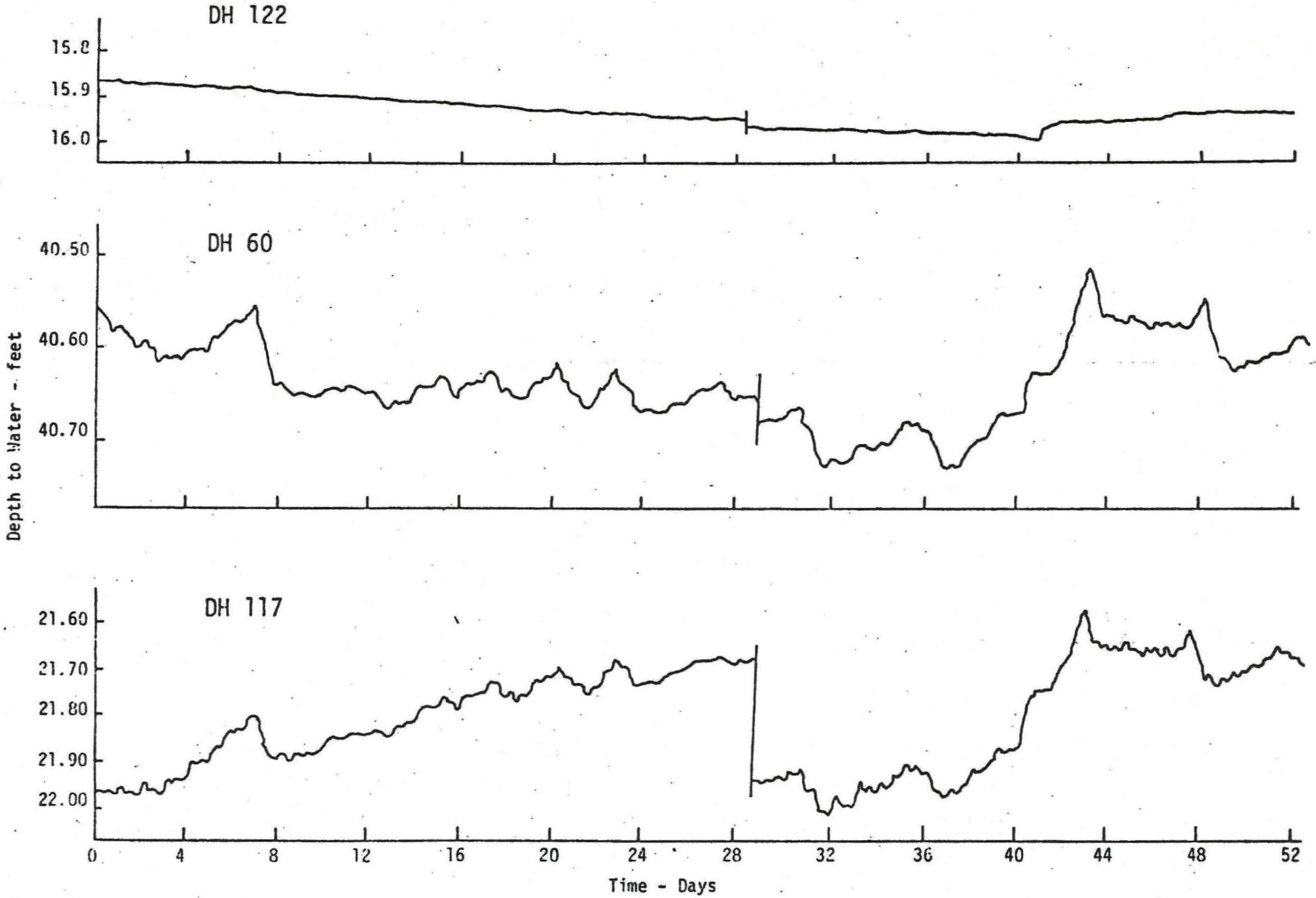


Figure 15. Water table fluctuation recordings.

3. Analysis of Aquifer Test Data

It is apparent from the discussions in the foregoing subsections that values of transmissivity, sotrage coefficient and apparent specific yield are required for several of the computations. Other important questions such as mine inflow, the extent of disturbance of the piezometric surface, and recovery time also require knowledge of the hydraulic coefficients. The use of the hydraulic coefficients in such calculations is outlined subsequently. In the present subsection, the analysis of the aquifer test data from which the coefficients are derived is discussed.

Aquifer test data analysis involves the graphical transformation of raw field data into calculated values of the aquifer parameters (Stallman, 1971). These aquifer parameters may be obtained from the observation of two relationships that occur during an aquifer test (Johnson Inc., 1974): 1) The rate of drawdown with respect to time at any point within the cone of depression (time-deawdown graph); and 2) shape and position of the cone of depression with respect to distance at some time during the aquifer test (distance-drawdown graph).

The Theis, Jacob, recovery, and slug test methods are based on observation of the time-drawdown relationship and the distance-drawdown test method is based on observations of the distance-drawdown relationship. All methods of aquifer test data analysis discussed herein are based on the following assumptions (Stallman, 1971; Johnson Inc., 1972).

1. The aquifer is homogeneous and isotropic
2. The aquifer is of uniform thickness.
3. The pumping well completely penetrates the aquifer.
4. The natural groundwater gradient is negligible.
5. Laminar flow conditions exist throughout the aquifer.

6. The aquifer is of infinite areal extent.

7. The well has been properly developed.

8. The well discharge is equal to the aquifer discharge.

The impact of boundary effects and well development on aquifer test data analysis is discussed later. Certain additional assumptions are invoked for particular types of analysis.

<u>Theis Analysis</u> (adapted from McWhorter and Sunada, 1977) - The Theis method of aquifer test analysis uses the following procedures:

1. On transparent log-log paper, plot drawdown vs r^2/t (r is the distance between the pumping and observation wells). This is known as the field curve.

2. From Table 20 prepare a log-log plot of W(u) vs u. This is known as the type curve. Note, both the field and type curves must be plotted on the same size log-log paper.

3. Superimpose the field curve over the type curve keeping both axes parallel. Adjust the position of the field curve until a best fit is made between the field data and the type curve.

4. Select any arbitrary "match" point and record its related coordinates W(u), u from the type curve and s, r^2/t from the field curve (Fig.16).

5. The values of W(u), u, s, r^2/t corresponding to the match point are inserted into the following formulas to determine the transmissivity and storage coefficient (or apparent specific yield):

$$T = \frac{QW(u)}{4\pi s} \qquad\qquad S = \frac{4Ttu}{r^2}$$

where

Q = well discharge during the pump test,

s = drawdown,

S = storage coefficient or apparent specific yield,

Table 20. Values of W(u) (After Wenzel, 1942)

N/u	$N \times 10^{-15}$	$N \times 10^{-14}$	$N \times 10^{-13}$	$N \times 10^{-12}$	$N \times 10^{-11}$	$N \times 10^{-10}$	$N \times 10^{-9}$	$N \times 10^{-8}$	$N \times 10^{-7}$	$N \times 10^{-6}$	$N \times 10^{-5}$	$N \times 10^{-4}$	$N \times 10^{-3}$	$N \times 10^{-2}$	$N \times 10^{-1}$	N
1.0	33.9616	31.6590	29.3564	27.0538	24.7512	22.4486	20.1460	17.8435	15.5409	13.2383	10.9357	8.6332	6.3315	4.0379	1.8229	0.2194
1.5	33.5561	31.2535	28.9509	26.6483	24.3458	22.0432	19.7406	17.4380	15.1354	12.8328	10.5303	8.2278	5.9266	3.6374	1.4645	0.1000
2.0	33.2684	30.9658	28.6632	26.3607	24.0581	21.7555	19.4529	17.1503	14.8477	12.5451	10.2426	7.9402	5.6394	3.3547	1.2227	0.04890
2.5	33.0453	30.7427	28.4401	26.1375	23.8349	21.5323	19.2298	16.9272	14.6246	12.3220	10.0194	7.7172	5.4167	3.1365	1.0443	0.02491
3.0	32.8629	30.5604	28.2578	25.9552	23.6526	21.3500	19.0474	16.7449	14.4423	12.1397	9.8371	7.5348	5.2349	2.9591	0.9057	0.01305
3.5	32.7088	30.4062	28.1036	25.8010	23.4985	21.1959	18.8933	16.5907	14.2881	11.9855	9.6830	7.3807	5.0813	2.8099	0.7942	0.006970
4.0	32.5753	30.2727	27.9701	25.6675	23.3649	21.0623	18.7598	16.4572	14.1546	11.8520	9.5495	7.2472	4.9482	2.6813	0.7024	0.003779
4.5	32.4575	30.1549	27.8523	25.5497	23.2471	20.9446	18.6420	16.3394	14.0368	11.7342	9.4317	7.1295	4.8310	2.5684	0.6253	0.002073
5.0	32.3521	30.0495	27.7470	25.4444	23.1418	20.8392	18.5366	16.2340	13.9314	11.6280	9.3263	7.0242	4.7261	2.4679	0.5598	0.001148
5.5	32.2568	29.9542	27.6516	25.3491	23.0465	20.7439	18.4413	16.1387	13.8361	11.5330	9.2310	6.9289	4.6313	2.3775	0.5034	0.0006409
6.0	32.1698	29.8672	27.5646	25.2620	22.9595	20.6569	18.3543	16.0517	13.7491	11.4465	9.1440	6.8420	4.5448	2.2953	0.4544	0.0003601
6.5	32.0898	29.7872	27.4846	25.1820	22.8794	20.5768	18.2742	15.9717	13.6691	11.3665	9.0640	6.7620	4.4652	2.2201	0.4115	0.0002034
7.0	32.0156	29.7131	27.4105	25.1079	22.8053	20.5027	18.2001	15.8976	13.5950	11.2924	8.9899	6.6879	4.3916	2.1508	0.3738	0.0001155
7.5	31.9467	29.6441	27.3415	25.0389	22.7363	20.4337	18.1311	15.8280	13.5260	11.2234	8.9209	6.6190	4.3231	2.0867	0.3403	0.0000658
8.0	31.8821	29.5795	27.2769	24.9744	22.6718	20.3692	18.0666	15.7640	13.4614	11.1589	8.8563	6.5545	4.2591	2.0269	0.3106	0.0000376
8.5	31.8215	29.5189	27.2163	24.9137	22.6112	20.3086	18.0060	15.7034	13.4008	11.0982	8.7957	6.4939	4.1990	1.9711	0.2840	0.0000216
9.0	31.7643	29.4618	27.1592	24.8566	22.5540	20.2514	17.9488	15.6462	13.3437	11.0411	8.7386	6.4368	4.1423	1.9187	0.2602	0.0000124
9.5	31.7103	29.4077	27.1051	24.8025	22.4999	20.1973	17.8948	15.5922	13.2896	10.9870	8.6845	6.3828	4.0887	1.8695	0.2387	0.0000071

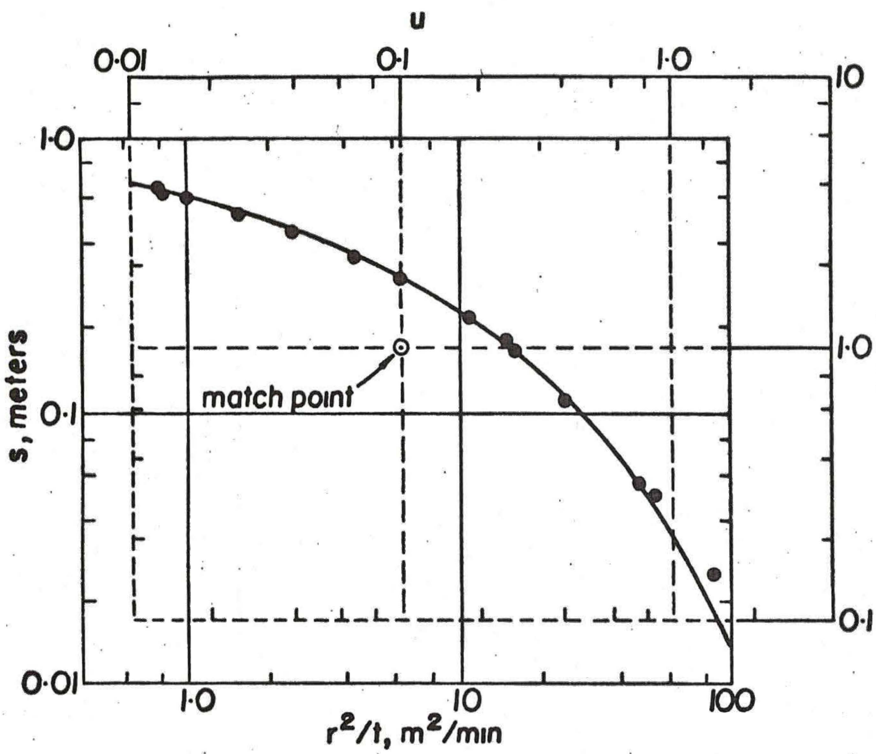


Figure 16. Matching the type curve with drawdown data.

T = transmissivity,

r = distance between pumping and observation wells,

$W(u), u$ = match point coordinates from the type curve.

Example (McWhorter and Sunada, 1977)

Estimate the transmissivity and apparent specific yield of an aquifer from the following data.

$r = 20$ meters $\qquad Q = 1.872\ m^3/min$

s(meters)	0.025	0.050	0.055	0.110	0.170	0.180	0.220
r^2/t (meters^2/min)	88.9	53.3	47.1	25.0	16.7	15.1	11.1

s	0.300	0.370	0.450	0.530	0.620	0.640	0.650
r^2/t	6.25	4.12	2.47	1.55	0.98	0.82	0.78

Following the procedures described previously, the data is plotted on log=log paper then superimposed on the type curve. Figure 16 illustrates the field curve superimposed on the type curve with a selected match point. The match point coordinates are:

$$W(u) = 1.0 \;,\quad u = 0.1 \;,\quad s = 0.183 \;,\quad r^2/t = 6.2 \;.$$

From before,

$$T = \frac{QW(u)}{4\pi s} = \frac{(1.872)(1.0)}{4\pi(0.183)} = 0.814\ m^2/min$$

$$S_{ya} = \frac{4Ttu}{r^2} = \frac{4(0.814)(0.1)}{6.2} = 0.053 \;.$$

In addition to the assumptions listed previously, this method assumes that the aquifer discharge is constant. In applications where the transmissivity is very low, the aquifer discharge to the well may not be constant, even for a constant pump discharge. This is because the pump derives a portion of its discharge from water standing in the well bore. Correction of the pump discharge, using measured drawdowns in the pumped well, may be necessary to determine an acceptably accurate value for Q in the above equations.

Jacob Analysis (adapted from McWhorter and Sunada, 1977) - The Jacob method is subject to the same restrictions as the Theis analysis. An additional restriction imposed on this method is that the test must be conducted for a sufficiently long time such that $u<0.01$, where $u = r^2/4\alpha t$ and $\alpha = T/S$ for confined aquifers; $\alpha = T/S_{ya}$ for unconfined aquifers.

The Jacob method uses the following procedures.

1. Using semi-log paper, plot drawdown on the coordinate axis vs time on the logarithmic axis (Fig. 17). The plot will be a straight line if the test was conducted for a sufficiently long period.

2. From this plot, compute the change in drawdown over one log cycle.

3. The change in drawdown over one log cycle is inserted into the following equation along with the other field data to determine transmissivity.

$$T = 2.303Q/4\pi\Delta s$$

Q = discharge
Δs = change in drawdown over one log cycle.

4. To determine the storage coefficient or apparent specific yield, extrapolate the straight line portion of the data plot to the horizontal axis (s=0). Determine the value of t_o where the straight line intersects the horizontal axis.

5. Insert the value of t_o along with the appropriate data into the following formula:

$$S = 2.246Tt_o/r^2$$

r = radial distance between the observation well and the pumping well,
T = transmissivity determined previously,
t_o = time where drawdown = 0,
S = storage coefficient (confined) or apparent specific yield (unconfined).

Example of Jacob Method (McWhorter and Sunada, 1977)

Given the following data, determine the transmissivity and the storage coefficient.

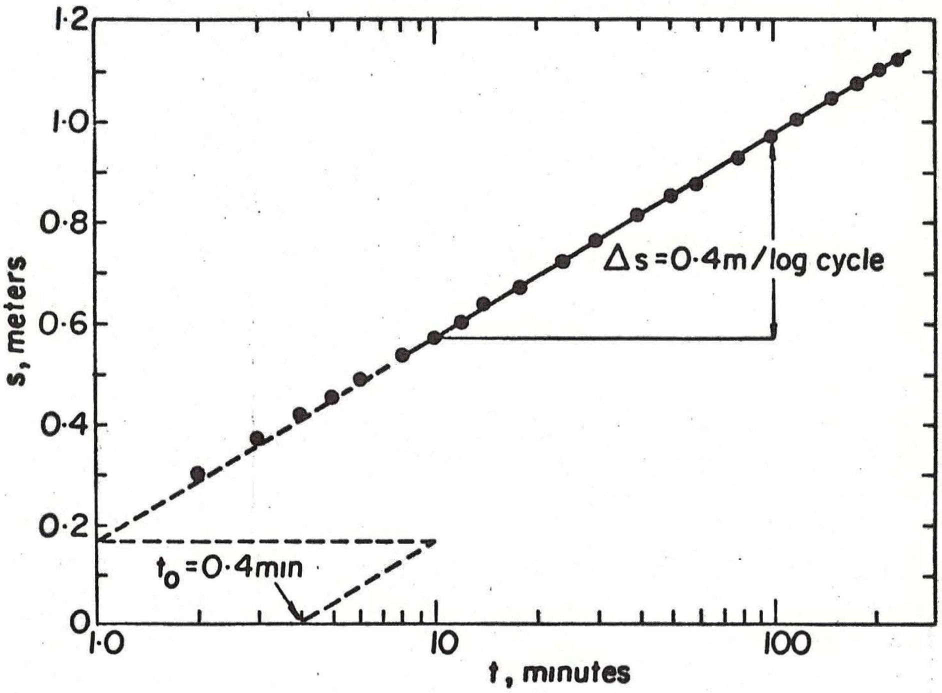


Figure 17. Example of the Jacob method for determining aquifer properties.

$r = 61$ meters $\qquad Q = 1.844\ m^3/min$

t(min)	1	2	3	4	5	6	8	10	12
s(meters)	0.200	0.300	0.370	0.415	0.450	0.485	0.530	0.570	0.600

t	14	18	24	30	40	50	60	80	100	120
s	0.635	0.670	0.720	0.760	0.810	0.850	0.875	0.925	0.965	1.000

t	150	180	210	240
s	1.045	1.070	1.100	1.120

The data are plotted as shown in Fig. 17. From the foregoing,

$$T = 2.303Q/4\pi\Delta s = [2.303(1.894)]/[4\pi(0.4)] = 0.868\ m^2/min \quad .$$

Extrapolation of the straight line yields t_0 = 0.4 minutes at s=0.

$$S = 2.246Tt_0/r^2 = [(2.246)(0.868)(0.4)]/(61)^2 = 2.0x10^{-4} \quad .$$

Before we can accept these results, we must be sure that $u \leq 0.01$. For a confined aquifer $u = Sr^2/4Tt$. The minimum test duration time for which $u \leq 0.01$ is given by $t = r^2S/4Tu = [(61)^2(2.0x10^{-4})]/[4(0.868)(0.01)] = 21$ min. Therefore, only data points for t>21 minutes should be used in the determination of the straight line. Using data for which u<0.01 causes a deviation of about 6% from the Theis analysis results.

Because of the restriction that u must be less than 0.01 for the Jacob method of analysis to be applicable, this procedure is usually used to analyze drawdown data collected on the pumped well itself. Thus, it is often used for the analysis of data from the drawdown/specific capacity type test that was discussed previously. Again, well-bore storage is likely to be a significant source of error in very tight aquifers unless the pump discharge is appropriately corrected.

Specific Capacity Analysis (adapted from Walton, 1970; USDI, 1977) - No attempt is made in this method to obtain values for the storage coefficient or apparent specific yield. Rather the procedure is to estimate an appropriate value for the storage coefficient based upon whether the aquifer is confined or unconfined and from experience in the area (if

any). A storage coefficient of 10^{-4} and an apparent specific yield of 0.1 will suffice if no information is available. Transmissivity T is plotted against corresponding values for specific capacity Q/s on log-log paper from the equation

$$Q/s = 4T/[\ln(\frac{4\pi T}{Sr_w^2} - 0.5772)] \quad ,$$

using the estimated value for S and a number of arbitrary values of T. The radius of the well is r_w. The value of time used in the computation is the pumping time at which the drawdown s was measured. The value of transmissivity that corresponds to the observed specific capacity is read from the graph.

The USDI (1977) reference presents a table from which the transmissivity can be estimated from knowledge of only specific capacity. The value so obtained is only a rough estimate.

Recovery Test Analysis (adapted from McWhorter and Sunada, 1977) - The recovery test is conducted immediately after the pump is shut off at the end of the pump test. An additional restriction imposed on this method is that the value of u must be less than 0.01, where $u = r^2/4\alpha t$ as stated previously.

The recovery test uses the following procedures.

1. Record the total length of pumping time when the pump is shut off (t_p).

2. Using semi-log paper, plot drawdown on the coordinate axis vs $t/t-t_p$ on the logarithmic axis (Fig. 18). Note, t is the time since pumping began, t_p is the total pumping time ($t>t_p$).

3. From this plot, compute the change in drawdown over one log cycle.

4. Insert the change in drawdown over one log cycle into the following equation to determine transmissivity.

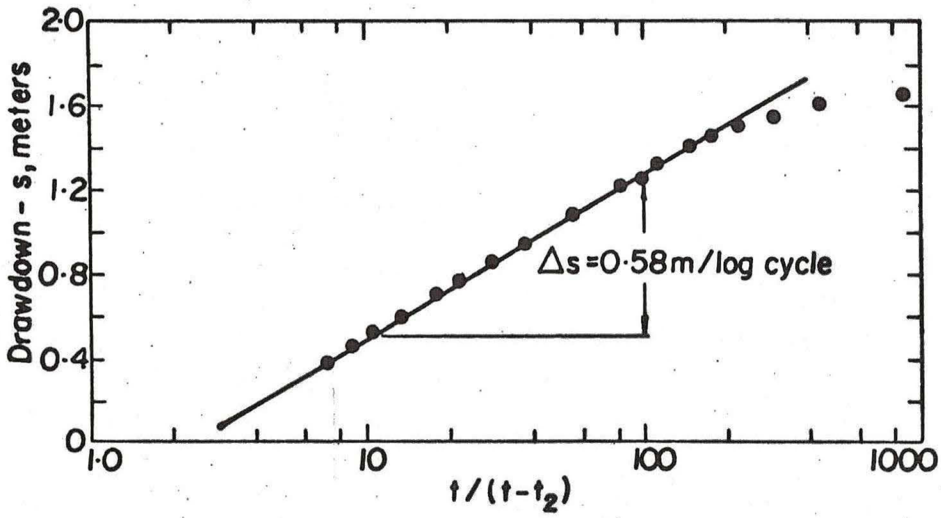


Figure 18. Water levels in a recovery test.

$T = 2.303Q/4\pi\Delta s$.

5. To determine the storage coefficient or apparent specific yield, extrapolate the straight line portion of the data plot to the horizontal axis. Determine t_o at the intersection of the straight line and horizontal axis.

6. Insert the value of t_o into the following formula:

$S = 2.246Tt_o/r^2$

r = distance between observation and pumping wells,
T = transmissivity,
t_o = time when drawdown = 0,
S = apparent specific yield or storage coefficient.

Example of Recovery Method (McWhorter and Sunada, 1977)

Given the following data determine the transmissivity and the storage coefficient.

$Q = 1.79\ m^3/min$, $r = 4.6\ m$, pumping time $t_p = 443$ min .

s(meters)	1.640	1.595	1.535	1.490	1.445	1.400	1.305	1.235	1.200
t(min)	443.5	444	444.5	445	445.5	446	447	447.5	448.5

s	1.060	0.930	0.845	0.755	0.700	0.590	0.521	0.451	0.384
t	451	455	459	464	469	479	489	499	514

Calculate $t/t-t_p$ for each of the above data points and plot as shown in Fig. 18. From the foregoing,

$T = 2.303Q/4\pi\Delta s = [2.303(1.79)2/[4\pi(0.58)] = 0.566\ m^2/min$.

Extrapolation of the straight line yields $t/t-t_p = 2.2$ min. From before,

$S = 2.246Tt_o/r^2 = [2.246(0.566)(2.2)]/(4.6)^2 = 0.13$.

Again the pump discharge may require correction to determine an appropriate value for Q in tight aquifers.

Slug test Analysis - Three methods of slug test analysis as proposed by Papadopulos et al. (1973), Cooper et al. (1967), and by Hvorslov (1951) are treated in this section.

The method proposed by Papadopulos et al. (1973) is as follows (adapted from McWhorter and Sunada, 1977).

1. On rectangular coordinate paper plot the residual built up of the water level due to a slug injection vs inverse time (Fig. 19).

2. Select any arbitrary point on the curve of $-s$ vs $1/t$. The coordinate of the point $(-s, 1/t)$ is inserted into the following equation to determine T.

$$T = V/4\pi t(-s)$$

v = slug volume,
t = time,
s= build up due to the slug injection.

Example (McWhorter and Sunada, 1977)

Determine the transmissivity from the following data.

$V = 0.148\ m^3$

$-s$(cm)	7.9	7.6	6.1	5.2	4.9	4.6	4.3	3.7	3.4
$1/t(min^{-1})$	0.800	0.750	0.667	0.521	0.461	0.435	0.413	0.361	0.333

$-s$	3.0	2.8	2.4	2.1	1.8	1.5	1.2	0.9
1/t	0.300	0.265	0.231	0.212	0.183	0.146	0.117	0.077

This data is plotted on coordinate paper as shown in Fig. 19. A point on the line in Fig. 19 is selected arbitrarily; in this case the coordinates of the point are $-s$ = 6.3 cm, 1/t = 0.6. From the foregoing,

$$T = V/4\pi t(-s) = 0.148/[4\pi(0.6)(6.3/100) = 0.11\ m^2/min\ .$$

Note this method does not provide a reliable determination of the storage coefficient (Cooper et al., 1967) and does not account for changes in well-bore storage.

The method of analysis as proposed by Cooper at al. (1967) is as follows.

1. On semi-log paper plot H/H_0 on the arithmetic axis vs time on logarithmic axis (field curve) where

H_0 = the buildup of the water level at time t=0 due to a slug injection,

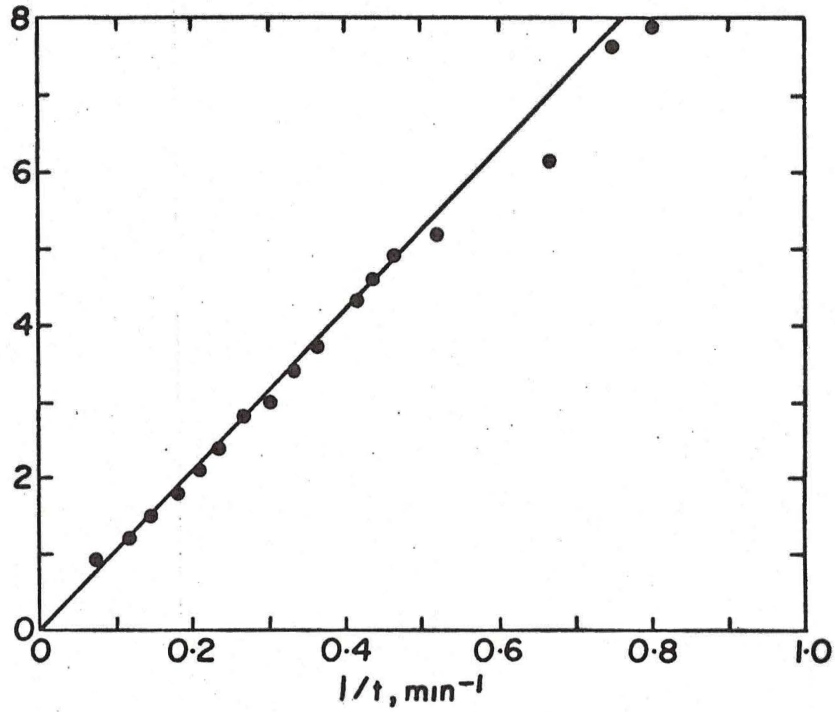


Figure 19. Response to a slug injection.

H = the residual water table buildup some time t after injection.

2. From Table 21 prepare a semi-log plot of H/H_o vs Tt/r^2 (type curve), where r = radius of well casing, T = transmissivity, and t = time.

3. Superimpose the field curve on the type curve keeping the horizontal axes coincident. Adjust the position of the field curve so as to achieve the best fit of data to the type curves (see Fig. 20).

4. Select an arbitrary "match" point and read the corresponding values of t (from the field curve) and Tt/r^2 (from the type curve).

5. Insert the corresponding match point values for t and Tt/r^2 into the following equation and solve for T.

$$T = [(Tt/r^2)r^2]/t$$

T = transmissivity,
r = well casing radius,
t = time coordinate on the field curve of the match point,
Tt/r^2 = the value of Tt/r^2 on the type curve corresponding to the match point.

Example (Cooper et al., 1967)

Given the test data listed in Table 22, determine the transmissivity. A plot of H/H_o vs t superimposed on the type curve is shown in Fig. 20. The coordinates of the match point are determined from Fig. 20 to be $Tt/r^2 = 1.0$, t = 11 sec. From the foregoing,

$$T = [(Tt/r^2)r^2]/t = [1(7.6)^2]/11 = 5.3\ cm^2/sec = 5.3x10^{-4}\ m^2/min.$$

Note this method does not provide a reliable determination of the storage coefficient, S (Cooper et al., 1967).

Slug test as proposed by Hvorslev (1951) is as follows.

1. On semi-log paper plot H/H_o on the logarithmic axis vs time on the arithmetic axis as shown in Fig. 21. H_o, the buildup of water level at time zero, is best determined as follows. Plot the buildup H vs time on semi-log paper as illustrated in Fig. 22. Extrapolate the straight line position of the plot to time t=0 to determine H_o, the initial buildup

Table 21. Values of H/H_0 for a Well of Finite Diameter (after Cooper et al., 1967)

Tt/r_c^2	H/H_0 $\alpha = 10^{-1}$	$\alpha = 10^{-2}$	$\alpha = 10^{-3}$	$\alpha = 10^{-4}$	$\alpha = 10^{-5}$
1.00×10^{-3}	0.9771	0.9920	0.9969	0.9985	0.9992
2.15×10^{-3}	0.9658	0.9876	0.9949	0.9974	0.9985
4.64×10^{-3}	0.9490	0.9807	0.9914	0.9954	0.9970
1.00×10^{-2}	0.9238	0.9693	0.9853	0.9915	0.9942
2.15×10^{-2}	0.8860	0.9505	0.9744	0.9841	0.9888
4.64×10^{-2}	0.8293	0.9187	0.9545	0.9701	0.9781
1.00×10^{-1}	0.7460	0.8655	0.9183	0.9434	0.9572
2.15×10^{-1}	0.6289	0.7782	0.8538	0.8935	0.9167
4.64×10^{-1}	0.4782	0.6436	0.7436	0.8031	0.8410
1.00×10^{0}	0.3117	0.4598	0.5729	0.6520	0.7080
2.15×10^{0}	0.1665	0.2597	0.3543	0.4364	0.5038
4.64×10^{0}	0.07415	0.1086	0.1554	0.2082	0.2620
7.00×10^{0}	0.04625	0.06204	0.08519	0.1161	0.1521
1.00×10^{1}	0.03065	0.03780	0.04821	0.06355	0.08378
1.40×10^{1}	0.02092	0.02414	0.02844	0.03492	0.04426
2.15×10^{1}	0.01297	0.01414	0.01545	0.01723	0.01999
3.00×10^{1}	0.009070	0.009615	0.01016	0.01083	0.01169
4.64×10^{1}	0.005711	0.005919	0.006111	0.006319	0.006554
7.00×10^{1}	0.003722	0.003809	0.003884	0.003962	0.004046
1.00×10^{2}	0.002577	0.002618	0.002653	0.002688	0.002725
2.15×10^{2}	0.001179	0.001187	0.001194	0.001201	0.001208

Table 22. Rise of Water Level in Dawsonville Well after Simultaneous Withdrawal of Weighted Float (r-7.6 cm)

t (sec)	$1/t$	Head (m)	H (m)	H/H_0
−1		0.896		
0		0.336	0.560	1.000
3	0.333	0.439	0.457	0.816
6	0.167	0.504	0.392	0.700
9	0.111	0.551	0.345	0.616
12	0.0833	0.588	0.308	0.550
15	0.0667	0.616	0.280	0.500
18	0.0556	0.644	0.252	0.450
21	0.0476	0.672	0.224	0.400
24	0.0417	0.691	0.205	0.366
27	0.0370	0.709	0.187	0.334
30	0.0333	0.728	0.168	0.300
33	0.0303	0.747	0.149	0.266
36	0.0278	0.756	0.140	0.250
39	0.0256	0.765	0.131	0.234
42	0.0238	0.784	0.112	0.200
45	0.0222	0.788	0.108	0.193
48	0.0208	0.803	0.093	0.166
51	0.0196	0.807	0.089	0.159
54	0.0185	0.814	0.082	0.146
57	0.0175	0.821	0.075	0.134
60	0.0167	0.825	0.071	0.127
63	0.0159	0.831	0.065	0.116

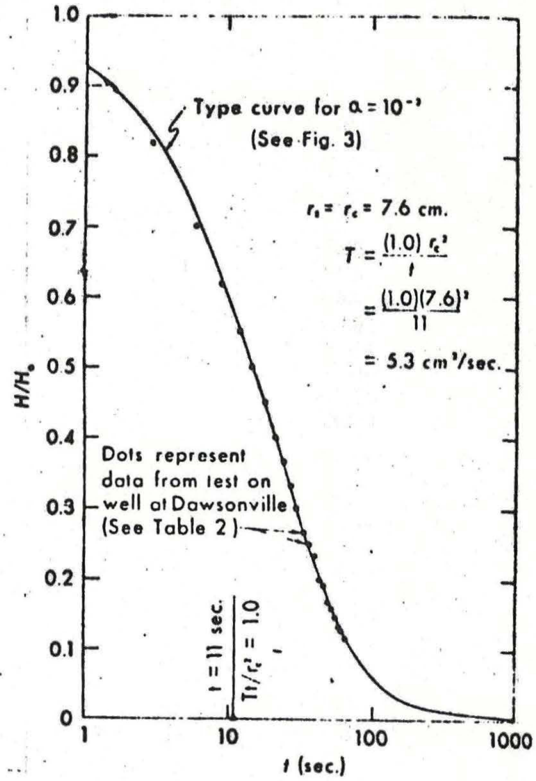


Figure 20. Plot of data from test at Dawsonville, Georgia, superposed on type curve. (After Cooper et al., 1967)

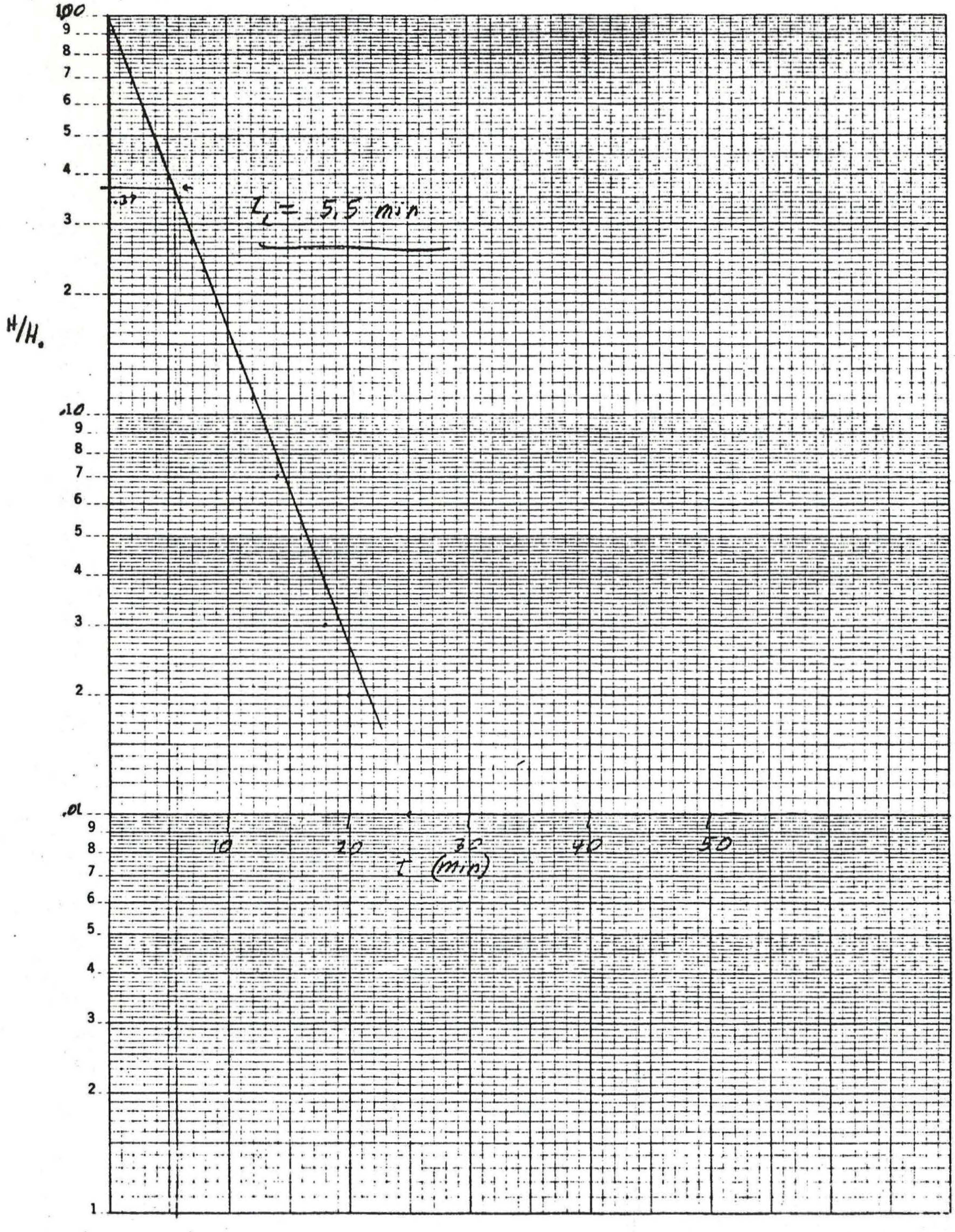


Figure 21. Time lag plot.

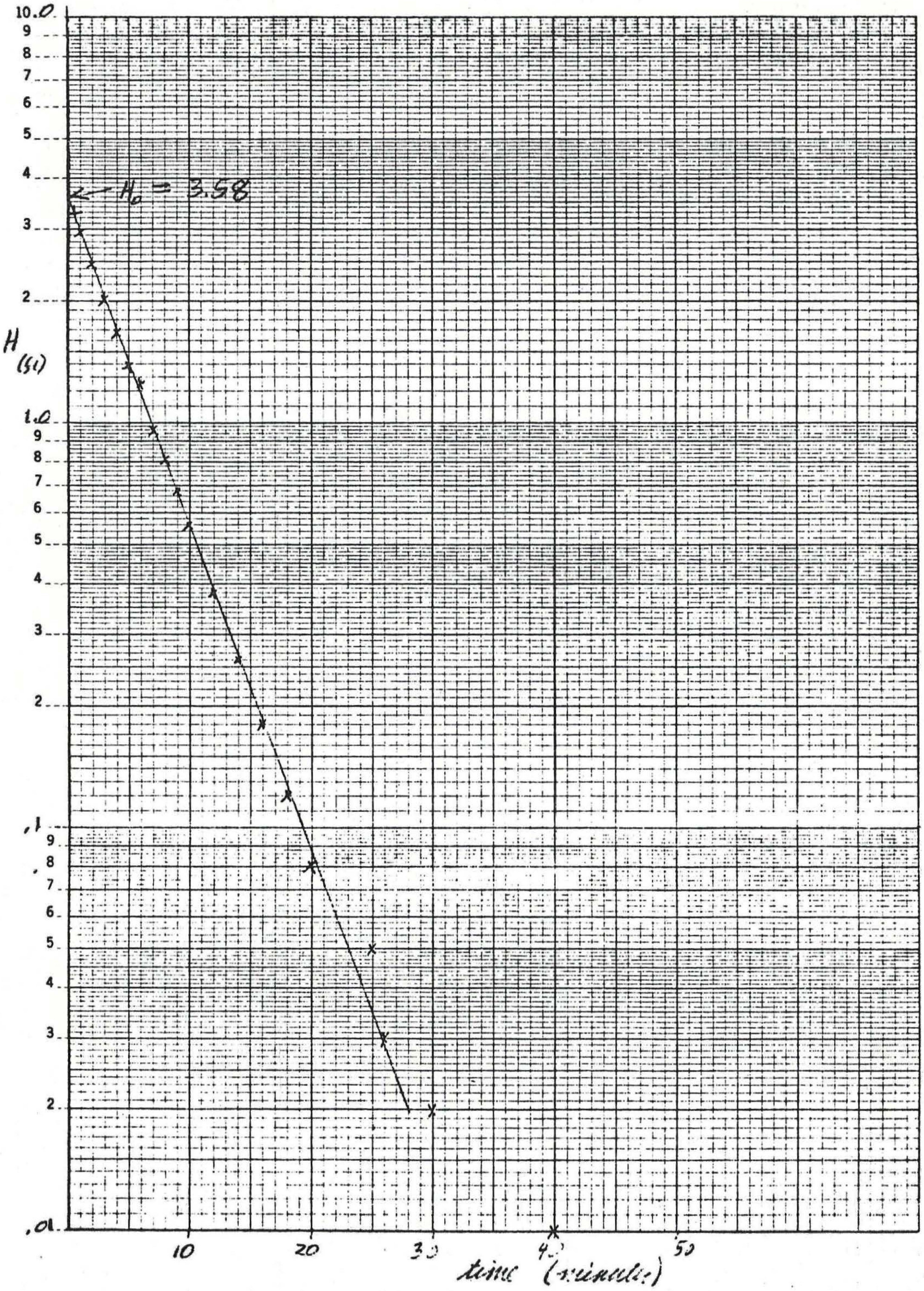


Figure 22. Example of the determination of H_o.

due to a slug injection at time zero. Once H_o is determined, values of H/H_o can be calculated and plotted as in Fig. 21.

2. From the semi-log plot of H/H_o vs t, determine the coordinates of t_L, the time lag, corresponding to $H/H_o = 0.37$ (Fig. 21).

3. Determine the coefficient C (Fig. 23) corresponding to value of L/r_w derived from the well construction data where L = screen length, r_w = well radius or radius of well plus the gravel pack.

4. Insert the coefficient C into the following equation to determine $\ln R_e/r_w$.

$$\ln R_e/r_w = \left[\frac{1.1}{\ln H_w/r_w} + \frac{C}{L/r_w} \right]^{-1} \quad \text{(Bouwer and Rice, 1976)}$$

where R_e = the effective radius of buildup, r_w = well radius or radius of well and aquifer pack (if known), L = screen length, and H_w = distance between the bottom of the well and the static groundwater surface (see Fig. 24 for the relation between H_w, r_w, L).

4. Insert the values of time lag (t_L), $\ln R_e/r_w$, and the well casing diameter into the following equation to determine K (for completely penetrating well).

$$K = \frac{d^2 \ln R_e/r_w}{8Lt} \quad \text{(Hvorslev, 1951)}$$

d = well casing diameter,
$\ln R_e/r_w$ = described in steps 3 and 4,
L = screen length,
t = time,
K = hydraulic conductivity.

<u>Example of the Hvorslev Method</u>

Given the following well construction and slug test data, determine the hydraulic conductivity.

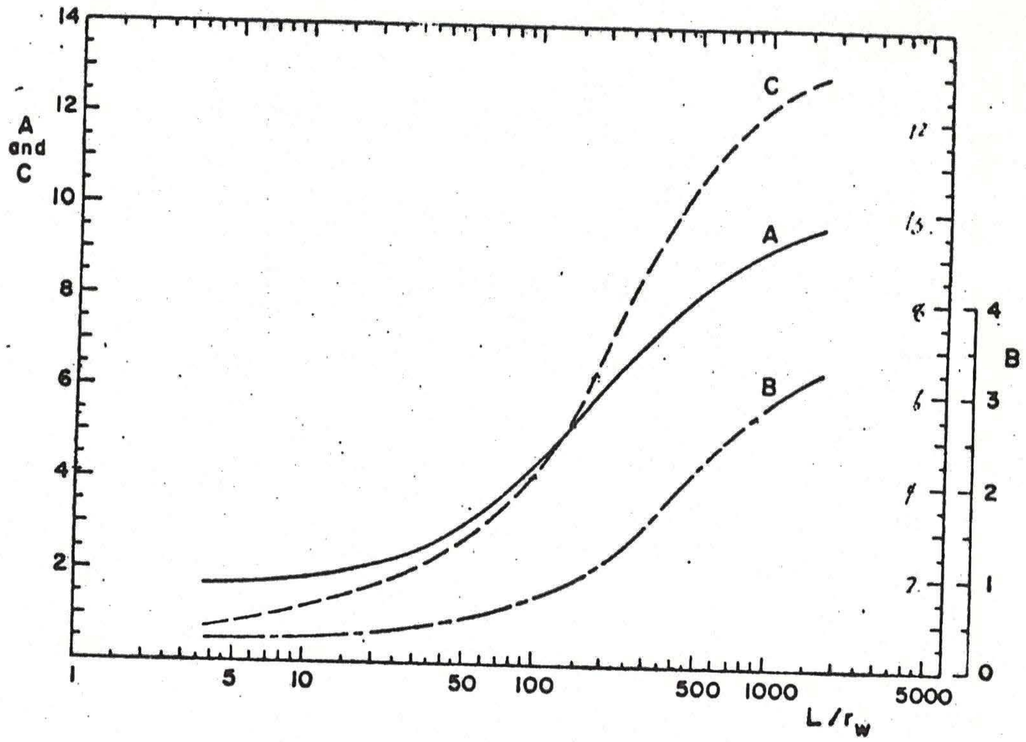


Figure 23. Curves relating coefficients A, B, and C to L/r_w.

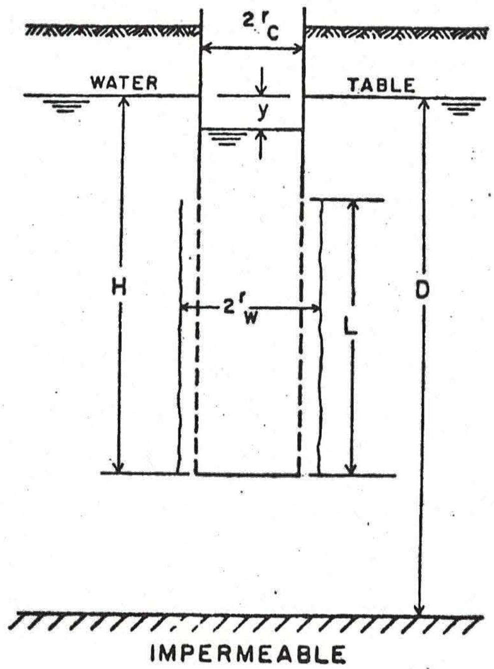


Figure 24. Geometry and symbols of a partially penetrating, partially perforated well in unconfined aquifer with gravel pack or developed zone around perforated section.

$d = 0.42$ ft , $L = 20$ ft , $r_w = 0.21$ ft , $H_w = 94.08$ ft .

H(feet)	3.27	2.94	2.44	2.01	1.68	1.39	1.24	0.96	0.81	0.68	0.56
t(min)	0.5	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0

H	0.38	0.26	0.18	0.12	0.08	0.05	0.03	0.02	0.01
t	12.0	14.0	16.0	18.0	20.0	25.0	26.0	30.0	40.0

A plot of H vs t is shown in Fig. 22. H_o is determined by extrapolating the straight portion of this plot to time t=0. From Fig. 22 $H_o = 3.58$ ft. The time lag t_L is 5.5 minutes as shown in Fig. 21. From Fig. 22 the value of C corresponding to $L/r_w = 95.2$ is ≈ 4.25. From before

$$\ln R_e/r_w = \left[\frac{1.1}{\ln H_w/r_w} + \frac{C}{L/r_w} \right]^{-1} = \left[\frac{1.1}{\ln 94.08/0.21} + \frac{4.25}{20/0.21} \right]^{-1}$$

$$= 4.45 \quad .$$

Therefore, the hydraulic conductivity is

$$K = [d^2 \ln R_e/r_w]/8Lt_L = [(0.42)^2(4.45)]/[8(20)(5.25)] = 9.35 \text{ ft/min}$$

$$= 1.35 \text{ ft/day} \quad .$$

Note $T = K\cdot b$ where T = transmissivity, K = hydraulic conductivity, and b = aquifer thickness. If the aquifer thickness is the same as the screen length (L=20 ft), then the transmissivity is

$$T = K\cdot b = (1.35)(20) = 26.9 \text{ ft}^2/\text{day}.$$

4. <u>Effects of Boundary Conditions and Well Construction on Aquifer Test Results</u>

Aquifer boundary conditions are rarely known at the field site prior to conducting the aquifer test. Any boundary effects must be recognized by the field investigator in order to avoid serious errors in the calculation of the aquifer parameters. Figures 25 and 26 illustrate the effect of recharge and impervious boundary conditions on the time-drawdown and distance-drawdown curves, respectively. The effects of these boundary conditions are summarized in Table 23 (Johnson Inc., 1974, p. 132). Recharge/boundary effects may be caused by nearby rivers or lakes, vertical

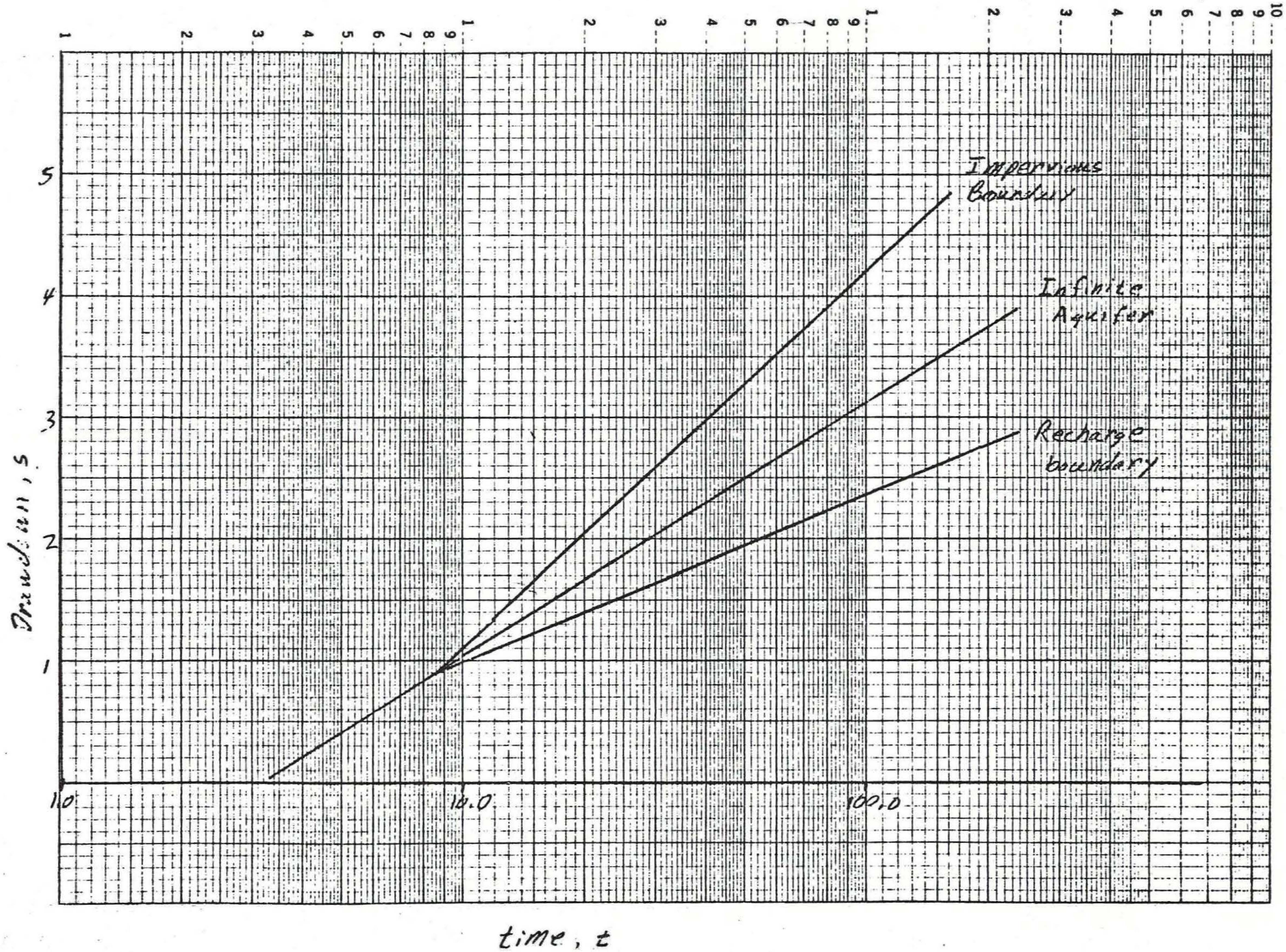


Figure 25. Effects of boundaries on drawdown vs. time.

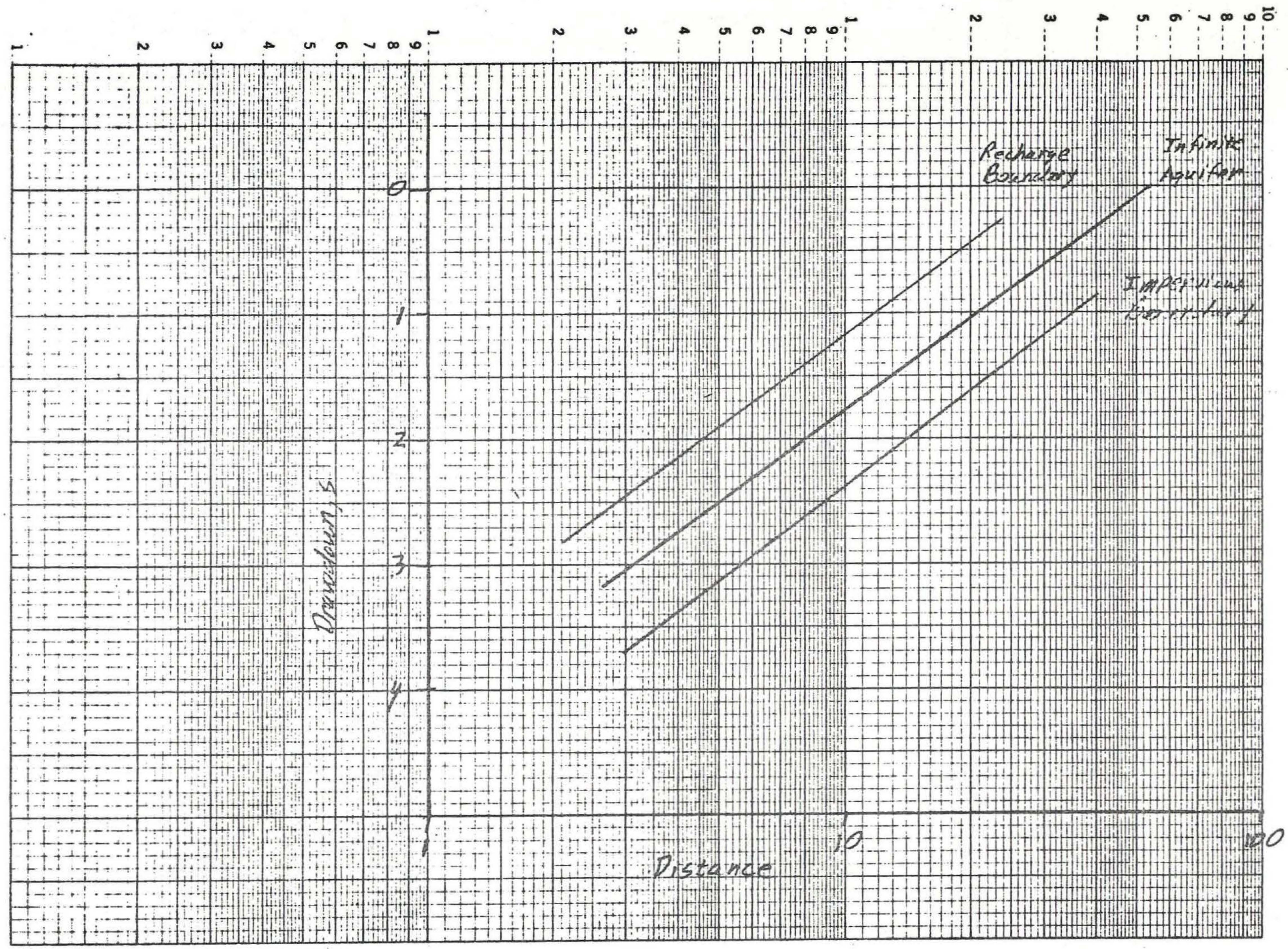


Figure 26. Effects of boundaries on drawdown vs. distance.

Table 23. Comparisons of Recharge and Boundary Effects on Semilog Diagrams

Time-Drawdown Graph	Distance-Drawdown Graph
Recharge Effect During Pumping Test	
1. Slope of graph becomes flatter. If transmissibility is calculated on the basis of the flatter slope it will be higher than the true value.	1. Slope of straight line remains almost unchanged. Aquifer transmissibility calculated from the graph is usually close to its true value.
2. Extending straight line of flatter slope results in an erroneous value of t_0 making it too low. A calculation using this figure gives a value for the storage coefficient that is smaller than the correct one.	2. Straight line is displaced upward. Extension to zero drawdown gives a value of r_0 which when used to compute storage coefficient results in a value higher than the correct one.
Boundary Effect During Pumping Test	
Time-Drawdown Graph	**Distance-Drawdown Graph**
1. Slope of graph becomes steeper. If transmissibility is calculated on the basis of the steeper slope it will be lower than the true value.	1. Slope of straight line remains almost unchanged. Aquifer transmissibility calculated from the graph is usually close to its true value.
2. Extending line of steeper slope results in erroneous value of t_0 which is too high. A calculation using this figure gives a storage coefficient that is larger than its correct value.	2. Straight line is displaced downward. Extension to zero drawdown gives erroneous value of r_0 which makes calculated value of storage coefficient smaller than the correct one.

infiltration from overlying zones, and increases in aquifer thickness or hydraulic conductivity. Impermeable boundary effects may be caused by geologic fault zones, decrease in aquifer thickness (pinch out), decrease in hydraulic conductivity, and impermeable bedrock. If boundary effects are apparent during the aquifer test, then the aquifer parameters must be determined from test data collected prior to the time the boundary effects are observable in the data.

Proper well construction is critically important if the aquifer test is to provide data representative of the aquifer. The following well design and construction factors contribute to excessive drawdown during the aquifer test (Johnson Inc., 1974):

1. Well screens with insufficient open area.
2. Poor distribution of well screens.
3. Insufficient well screen length.
4. Inadequate well development.
5. Improper placement of the well screen.

Any one of these factors can significantly reduce the calculated values of transmissivity or hydraulic conductivity.

<u>Example Mine Inflow Computation</u> - Once the hydraulic coefficients are known, they can be used to estimate mine inflow and the extent to which the piezometric surface is disturbed. There exist a variety of ways in which this can be accomplished that range from simple idealizations to application of sophisticated models. The following is an example when the relatively simple idealization of one-dimensional inflow to a pit is applicable.

The inflow to a mine pit that cuts through an aquifer is given by

$$q = 2(12t/S_{ya}Th_o^2)^{-1/2} + q_o \quad ,$$

where q = inflow discharge per unit of pit length (both sides),

q_o = natural flow in undisturbed aquifer per unit of pit length,

t = time since inflow began,

S_{ya} = apparent specific yield,

T = transmissivit6,

h_o = initial saturated thickness of aquifer.

This equation is a special case of a more general result given by Bear (1972). The discharge predicted by this equation is the inflow discharge per unit of open pit. A mining plan is required to convert these values into actual discharges to be expected at any time. For example, suppose $S_{ya} = 0.05$, $T = 10$ ft^2/day, $h_o = 65$ ft, $q_o = 0$, and the mining plan calls for 1500 ft of pit to be open every 3 months until a total pit length of 7500 ft is achieved and the pit length is constant thereafter. Pit inflow as a function of time is computed by calculating the inflow from each segment of the pit, marking time for each segment from the time that the segment was opened. The contributions from each segment at any time after the opening of the first segment are calculated by adding the contributions from each individual section. The computations are summarized in Table 24. Q in this table is the discharge per unit of pit length (q) multiplied by the length of the open segment. The subscripts refer to the first, second, etc. segments of the pit. Q_{total} represents the inflow from the total length of open pit at any time. The maximum inflow discharge is 13,650 ft^3/day or about 70 gpm in this example.

The theory leading to the above equation also provides a means for estimating the distance from the pit to points where the piezometric surface remains essentially undisturbed. The equation is

$$L = (3Tt/S_{ya})^{1/2} \quad ,$$

Table 24. Example of Lateral Inflow Computation

Time Years	q $ft^3/ft\text{-}d$	Q_1	Q_2	Q_3 ft^3/d	Q_4	Q_5	Q_{total}
0.25	2.8	4200	-	-	-	-	4200
0.50	2.0	3000	4200	-	-	-	7200
0.75	1.6	2400	3000	4200	-	-	9600
1.00	1.4	2100	2400	3000	4200	-	11700
1.25	1.3	1950	2100	2400	3000	4200	13650
1.50	1.2	1800	1950	2100	2400	3000	11250
1.75	1.1	1650	1800	1950	2100	2400	9900
2.00	1.0	1500	1650	1800	1950	2100	9000
2.25	0.95	1425	1500	1650	1800	1950	8325

where L is the distance from the pit to the point where the drawdown of the piezometric surface is zero. Using the same numbers for T and S_{ya} as above, this equation predicts that inflow to the pit will cause the piezometric surface to be depressed to a distance of about 0.5 miles from the pit after 20 years.

The above equations and computations are presented to demonstrate one possible use of the hydraulic coefficients. Other uses exist and certainly there are many other ways to estimate pit inflow during mining. The above constitutes an example, not a recommendation.

Effect of Abandoned Mine on Piezometric Surface - Another aspect that is sometimes important in pre-mine planning and decision making is the extent to which the original piezometric surface will remain disturbed after the mine is abandoned. McWhorter and Rowe (1976) and Hamilton and Wilson (1977) provide approaches to this problem. McWhorter and Rowe (1976) idealize the abandoned mine area as a circle of radius R and area equal to the actual mined area. Their equation for the distance to which the post-mining piezometric head is different from the pre-mining value by an arbitrary amount is

$$r = \frac{R}{\sqrt{c}} \left(\left| \frac{K_o - K_i}{K_o + K_i} \right| \right)^{1/2}$$

where r = distance from the center of the mined area to points where post-mining piezometric head is different from the pre-mining value by an arbitrarily small fraction equal to c.

R = equivalent radius of the mined area.

c = ratio of the difference between pre-mining and post-mining values of piezometric head to the pre-mining value.

K_o = hydraulic conductivity outside the mined area.

K_i = hydraulic conductivity inside the mined area.

Use of the above equation requires that both K_o and K_i are known. Prior to mining, K_i is not known. Nevertheless, the maximum distance can be estimated by putting $K_i=0$ or $K_i=\infty$ for which

$$r = R\sqrt{c} \quad .$$

For example, the distance to which the post-mining piezometric head differs from the pre-mining value by 10 percent if $r = R/\sqrt{0.10} = 3R$.

The analysis also permits one to establish other limiting values that may be of interest. For example, it is shown that the maximum width of the downstream plume of ground water of modified quality is 4R. Also, post-mining flow through the mined area can be no greater than twice the pre-mining flow through the same area, regardless of how permeable the spoils are compared to the undisturbed aquifer.

The conditions under which the foregoing analyses are made are highly idealized relative to the conditions that can be expected to prevail in the field. The results should be expected to yield only order-or-magnitude estimates of the extent to which the long-term, post-mining ground water flow differs from the pre-mining condition. Hamilton and Wilson (1977) provide results similar to those discussed above for a variety of mine geometries.

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APPENDIX I

SOURCES OF GEOLOGICAL, HYDROLOGICAL, SOILS, AND RECLAMATION DATA

Abstracts of North American Geology, monthly, 1966-1971: Washington, U.S. Geological Survey.

Agronomy Abstracts. Abstracts of pepers presented at annual meetings. American Society of Agronomy: Madison, Wisconsin.

Annual summaries and/or yearbooks are published by most state geological surveys or bureaus.

Beatty, W. B., Mineral resources data in the western states: Palo Alto, California, Stanford Research Institute. 1962.

Black, C. A., (ed.), Methods of soil analysis, Part 2: American Society of Agronomy Monograph No. 9, 1965.

Chemical Abstracts. weekly: Columbus, Ohio, American Chemical Society. (Topics include minerals, mining, geology, and specific metals)

Chronic, J. B., Bibliography of theses written for advanced degrees in geology and related sciences at universities and colleges in the United States and Canada through 1957: Boulder, Colorado, Pruett Press, 1958.

Chronic, J. B., Bibliography of theses in geology, 1958-1963: Washington, - American Geological Institute, 1964.

Czapowskyj, M. W., Annotated bibliography on the ecology and reclamation of drastically distrubed areas. USDA Forest Service General Technical Reprot NE-21. Northeast Forest Experiment Station, 6816 Market St., Upper Derby, Pa., 1976

Dalsted, N. L. and Leistriz, F. L., A selected bibliography on surface coal mining and reclamation of particular interest to the Great Plains states: Ag. Econ. Misc. Report No. 16, North Dakota Ag. Experiment Station, 1973.

Dissertation Abstracts International, monthly: Ann Arbor, Michigan. University Microfilms.

Earth Sciences Research Catalog: Tulsa, Oklahoma, University of Tulsa. For the entire United States; indexed by area.

Economic Geology, Geology of ore deposits (abstracts of Russian Academy of Science articles) in several issues each year.

Frawley, M. L., Surface mined areas: control and reclamation of environmental damage. A bibliography USDI Office of Library Services, Bibliography Series 27, 1971.

Geoabstracts, bimonthly: Norwich, England, University of East Anglia. With a worldwide geographical and subject index in seven parts:
A. Landforms and the Quaternary
B. Climatology and hydrology
C. Economic geography (including minerals)
D. Social and historical geography
E. Sedimentology
F. Regional and community planning
G. Remote sensing and cartography.

Geocom Bulletin/Programs, monthly: London, Geosystems (Lea Associates). Abstracts and information on mathematical geology, exploration techniques, and computer methods in geoscience.

Geological Field Trip Guidebooks for North America: Washington, American Geological Institute, 1968.

Geochemical Abstracts, quarterly: Oxford, England, The Pergamon Press. Successor to Rock Mechanics Abstracts. Combined in 1974 with issues of the International Journal of Rock Mechanics and Mining Sciences.

Geoscience Abstracts, 1959-1966, and Geological Abstracts, 1953-1958, of the American Geological Institute, Washington, D.C.

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Given, I. A., Sources of information, in Cummins, A. B., and Given, I. A., eds., SME mining engineering handbook: New York, Am. Inst. Mining Metall. Petroleum Engineers, v. 2, sec. 35, p. 35-1-35-34, 1973. (Lists departments of mines, geologic surveys, societies, institutes, and their publications, by country and by U.S. state. Also lists major periodicals, directories, and yearbooks.)

Hoy, R., Sources of information, in, Lefond, S. J., ed., Industrial minerals and rocks. ed. 4: New York, Am. Inst. Mining, Metall. Petroleum Engineers, p. 1290-1305. 1975. (Lists industrial minerals publications and publishers.)

Journal of Soil and Water Conservation, bimonthly: Soil Conservation Society of America, Ankeny, Ohio.

Kaplan, S. R., Guide to information sources in mining, minerals, and geosciences: New York, Interscience Publishers, 599 p.,1965. (Part I lists names, addresses, function, and publications of national, state, and private associations dealing with mining; U.S. and foreign bureaus of mines are included. Part II describes available literature in books and journals by country and subject.)

Long, H. K., A bibliography of earth science bibliographies of the United States: Washington, American Geological Institute, 1971.

Mineral Trade Notes, monthly: Washington, U.S. Bureau of Mines. (Includes news of developments in foreign mining areas.)

Schaller, F. W., and Sutton, Paul (eds.), Reclamation of drastically disturbed lands: American Society of Agronomy, Madison, Wisconsin, 1978.

Soil Science Journal, bimonthly: Soil Science Society of America, Madison, Wisconsin.

The Minerals Yearbook, annually: Washington, U.S. Bureau of Mines. (Contains state and country summaries, with news of developments at major mines as well as commodity reviews).

USDA Agricultural Handbook No. 60, Diagnosis and improvement of Saline and Alkali Soils, Washington D. C., 1954.

USDA Agricultural Handbook No. 436, Soil Taxonomy: Soil Survey Staff, Washington, D. C., 1975.

Ward, D. C., Bibliography of theses in geology: Geoscience Abstracts, v. 7, no. 12, pt. 1, p. 103-129, 1965.

Ward, D. C., Bibliography of theses in geology, 1967-1970: Boulder, Colorado, Geol. Soc. America Spec. Paper 143, 1973.

Ward, D. C., and O'Callaghan, T. C., Bibliography of theses in geology, 1965-66: Washington, American Geological Institute, 1969.

Ward. D. C., and Wheeler, M. W., eds., Geologic reference sources: Metuchen, N. J., The Scarecrow Press, 453 p., 1972. (Covers general information by country and state.)

Wood, D. N., ed., Use of earth science literature: London, Butterworth and Co., 459 p., 1973. (This could be called "everything you might possibly want to know about geologic information sources." Detailed information is included on methods of literature search, with lists of regional information by country and state.)

APPENDIX II

UNITED STATES - STATE GEOLOGICAL SURVEYS AND BUREAUS OF MINES FOR THE ROCKY MT. REGION

Arizona Bureau of Mines
Univ. of Arizona
Tucson, Ariz. 85721

Colorado Geological Survey
1845 Sherman St.
Room 254
Denver, Colorado 80203

Idaho Bureau of Mines and Geology
Moscow, Idaho 83843

Montana Bureau of Mines and Geology
Montana College of Mineral Science and Technology
Butte, Montana 59701

New Mexico Bureau of Mines and Mineral Resources
Socorro, New Mexico 87801

North Dakota Geological Survey
Univ. Station
Grand Forks, N.D. 58202

South Dakota Geological Survey
Science Center
Univ. of South Dakota
Vermillion, S. D. 57069

Utah Geological and Mineral Survey
103 UGS Bldg.
Univ. of Utah
Salt Lake City, Utah 84112

Geological Survey of Wyoming
Box 3008, Univ. Station
Univ. of Wyoming
Laramie, Wyoming 82071

APPENDIX III

Codes for Abbreviations and Symbols Used In Construction of Lithologic Log (Figure 5 in Text)

BEDDING THICKNESS

H -	Homogenous (no lamination)
H - DM	Homogenous, distinctly mottled
H - IM	Homogenous, indistinctly mottled
L -	Laminated - < 1 cm thick
F -	Thin Bedded - 1-10 cm thick
M -	Medium Bedded - 10-30 cm thick
T	Thick Bedded - 30-100 cm thick
VT	Very Thick Bedded - > 100 cm thick
L/F	Thin bedded sets of cross-lamination; etc.

INDURATION

U -	Unconsolidated
I -	Indurated
IP -	Indurated but plastic
IS -	Indurated but shaly
IF -	Indurated but friable
WI -	Well indurated

SORTING

WS -	Well sorted
MWS -	Moderately well sorted
MS -	Moderately sorted
PS -	Poorly sorted

ROUNDNESS

A -	Angular
S -	Sub-rounded to Sub-angular
R -	Rounded

PERCENT LIMESTONE (SCALE OF 1-10)

<1	Trace of effervescence
1	Slight effervescence
3	Moderate effervescence
5	Strong effervescence
10	Very Strong effervescence
>10	Limestone

SAMPLE TYPE

T.S. - Thin section sample
S - Size sample
X - X-ray analysis sample
G - Growth study sample

ROCK TYPE AND ACCESSORY SYMBOLS

(see attached chart)

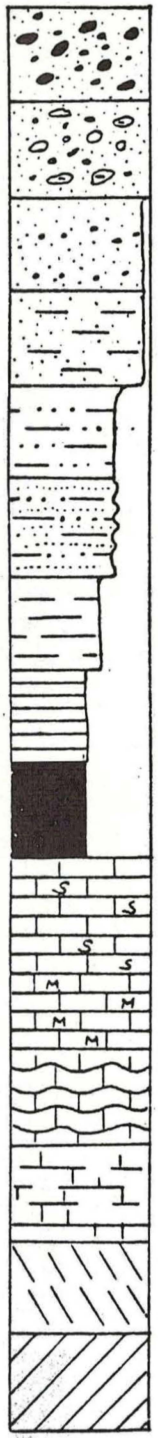
SEDIMENTARY STRUCTURE SYMBOLS

(see attached chart)

DESCRIPTION

Color, size, sorting, rock type, Sed. Str.,
Example: red, fine-grained, well sorted, sandstone, with horizontal laminations.

ROCK TYPE SYMBOLS



conglomerate

intraclastic conglomerate

sandstone (with granule layers)

clayey sandstone

siltstone

sandstone and siltstone

mudstone

claystone

coal or peat

limestone (sparry)

micritic limestone

algal limestone

marlstone (clayey limestone)

gypsum

lost core

ACCESSORY SYMBOLS

calcareous (>3%)

marcasite nodules

pyrite nodule

oxydized pyrite nodule

plant fragments and carbonaceous matter

pelletoids

limonitic nodules

\\\\ gypsum

organic partings

clay gall intraclasts

nodules

V glauconite

megafossils

mica

chert

R oxydized colors (reddish)

bentonite

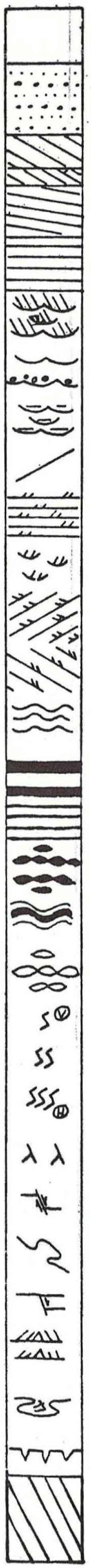
+ feldspar

clayey

iron oxide nodules

Mn manganese

SEDIMENTARY STRUCTURE SYMBOLS



"structureless" sand

interbedded sand and granule layers (horizontal bedding)

large scale cross-bedding (tabular)

low angle cross-bedding

parallel bedding

trough cross-bedding

scours (with channel lag)

scour and fill

downcutting surface

ripple-tabular x-lamination

ripple-trough cross-lamination

ripples in - drift

ripples on crossbeds

wavey bedding

coarsely interlayered sand and mud

alternating sand and mud

flaser bedding

wavey bedding

lenticular bedding

weak
moderate — Bioturbation
strong

rooting

microfaults

contorted (slumped) beds

growth faults

bimedal current directions

loadcasting

mudcracks

forset beds

APPENDIX IV

MANUFACTURERS AND DISTRIBUTORS

Listing of manufacturers and distributors who have been referred to in this report.

Acker Drill Company
P. O. Box 830
Scranton, Pennsylvania 18501

Boyle Bros.
P. O. Box 25068
1624 Pioneer Road
Salt Lake City, Utah 84125

Christensen Mining Products Division
Christensen Diamond Products Company
1937 South 300 West
Salt Lake City, Utah 84115

Joy Manufacturing Company
Montgomery Industrial Center
Montgomeryville, PA 18936

Longyear Company
925 Delaware Street, S.E.
Minneapolis, Minnesota 55414

Mobile Drilling Company, Inc.
3807 Madison Avenue
Indianapolis, Indiana 46227

Odgers Drilling, Inc.
Ice Lake Road
Iron River, Michigan 49935

Penndrill Manufacturing Division
Pennsylvania Drilling Company
P. O. Box 8562
Pittsburg, Pennsylvania 15220

Pitcher Drilling Company
75 Allemany Street
Daly City, California 94014

Reed Tool Company
105 Allen Street
P. O. Box 3641
San Angelo, Texas 76901

Reese Sales Company
P. O. Box 645
2301 Gibson Street
Bakersfield, California 93302

Soiltest, Inc.
2205 Lee Street
Evanston, Illinois 60202

Sprague and Henwood, Inc.
221 West Olive Street
Scranton, PA 18501

Triefus Industries (W.A.) Co.
Sidney, Australia